

# BNL VLBL Study Update

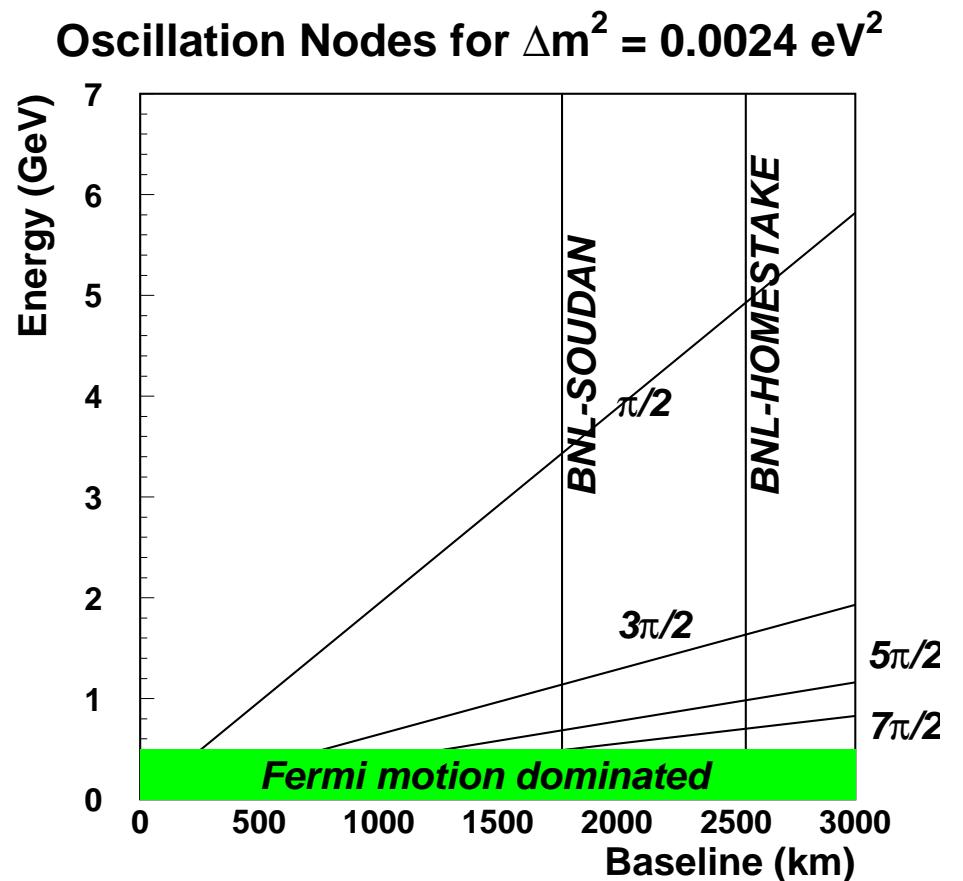
Outline:

- Benefits of the VLBL concept
- Review of the Components
- Separating Multiple Effects
- Current Analysis (Diwan)
- Confronting the Challenges

# Why the V in VLBL?

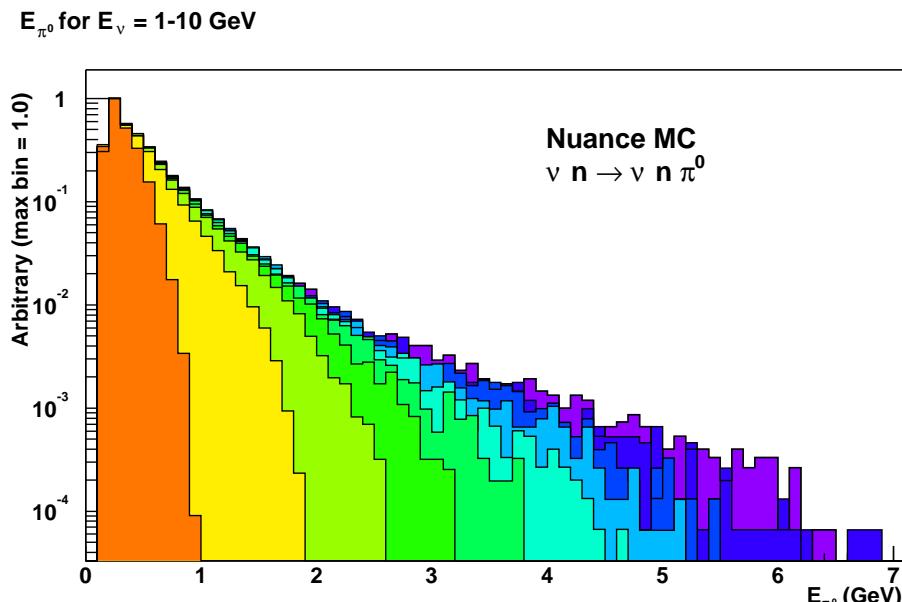
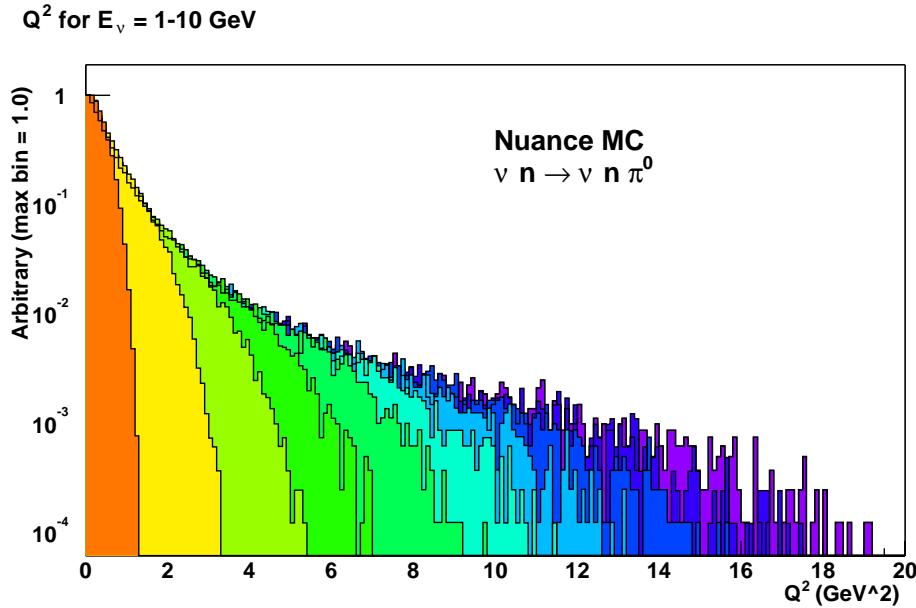
With Very Long Baselines:

- Multiple oscillations are resolvable.
- Oscillations in an energy region where:
  - Cross sections are higher
  - Fermi motion less detrimental to energy resolution
- For  $\Delta m^2$  in SK region, need baseline  $> 2000$  km.



Need wide band, high energy  $\nu$  beam, but what about NC  $\nu_e$  bkg? →

# NC Feed Down



C.W.: “NC bkg to  $\nu_e$  is large above 1 GeV”  
 Yes, but it is mostly gone above 2 GeV.

Plots show:

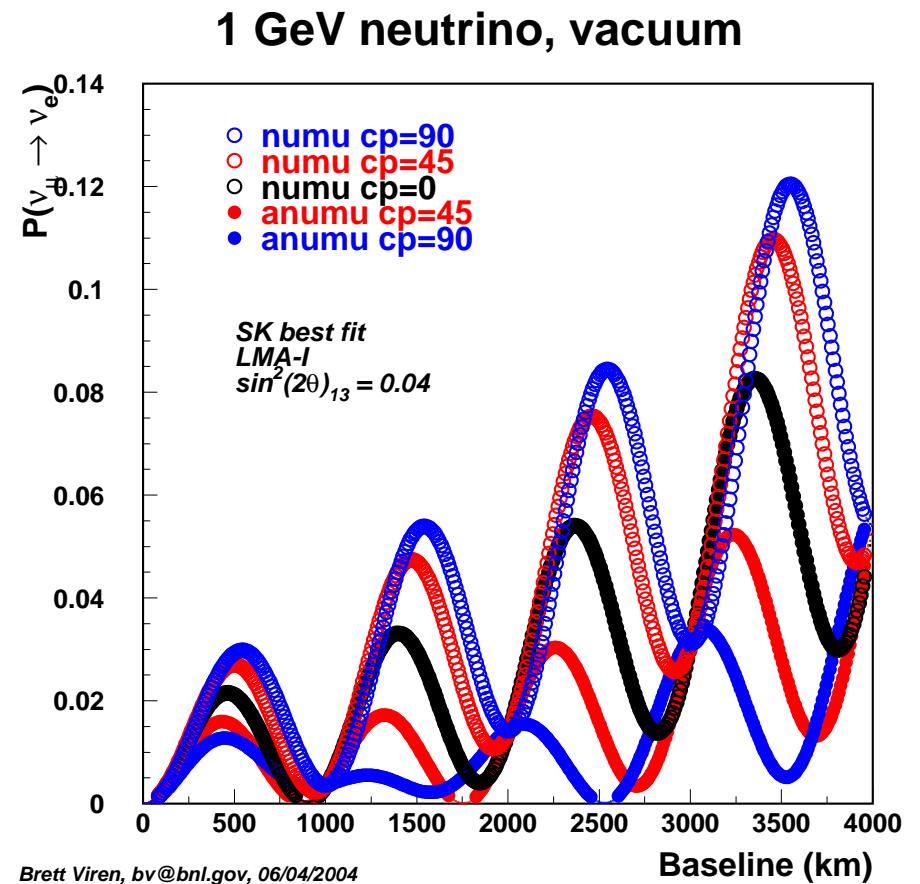
- Nuance MC
- $Q^2$  (top) and  $E_{\pi^0}$  (bottom) for single- $\pi$  NC events
- Each color band: mono-energetic neutrinos, 1-10 GeV in 1 GeV steps.
- Above 2 GeV, background reduction is  $> 50\times$ , naturally

⇒ Put signal above 2 GeV, but that means very long baseline, what about statistics? →

# Extra Long Baselines and CP Asymmetry

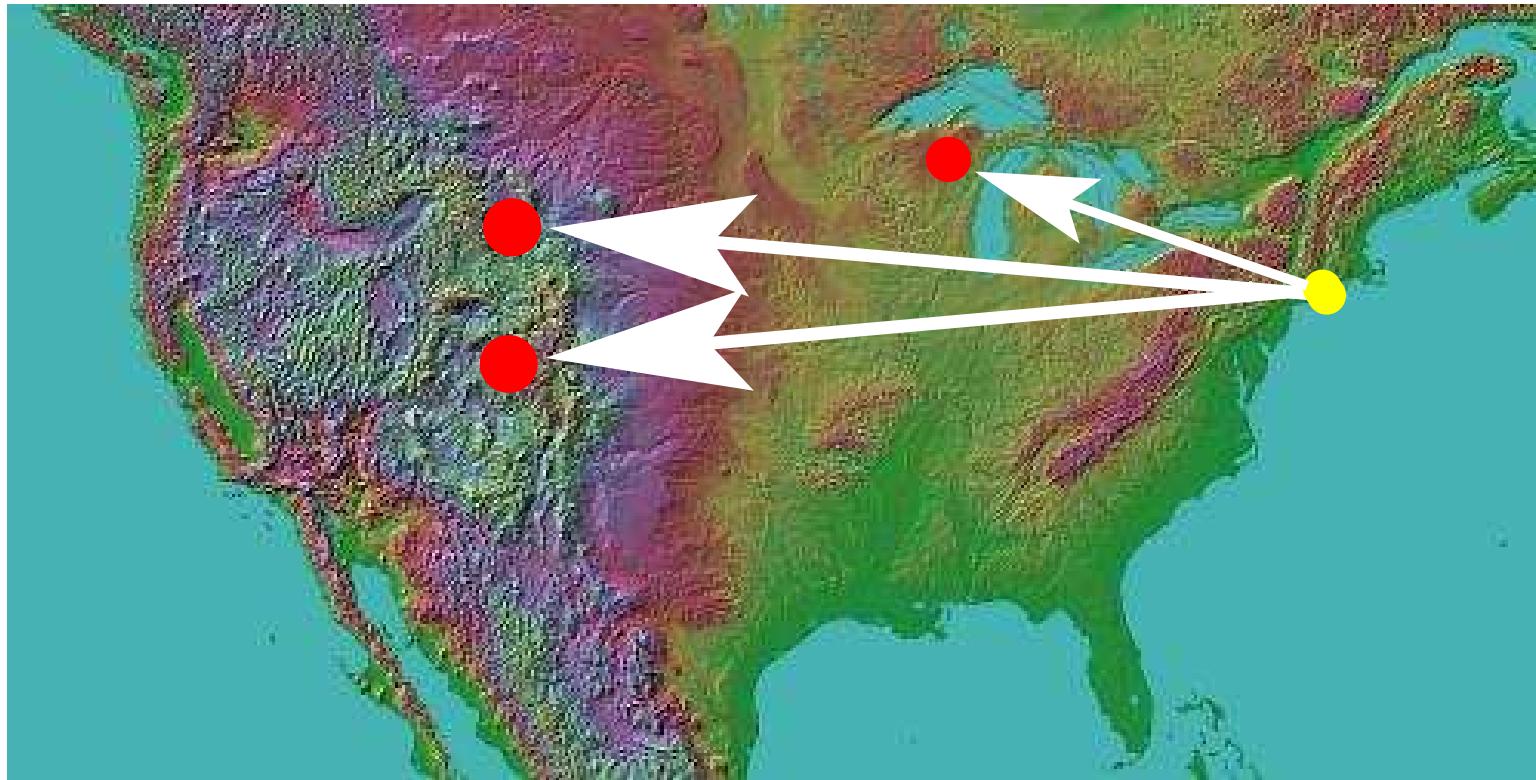
Marciano (hep-ph/0108181):

- Yes, statistics fall off with baseline ( $1/L^2$ )
- but, CP asymmetry grows with baseline ( $L$ )
- so,  $FOM = A^2 N_\nu / (1 - A^2)$  is  $\sim$ constant



Message: don't be afraid to get high and go long!

## Which Baselines are Very Long



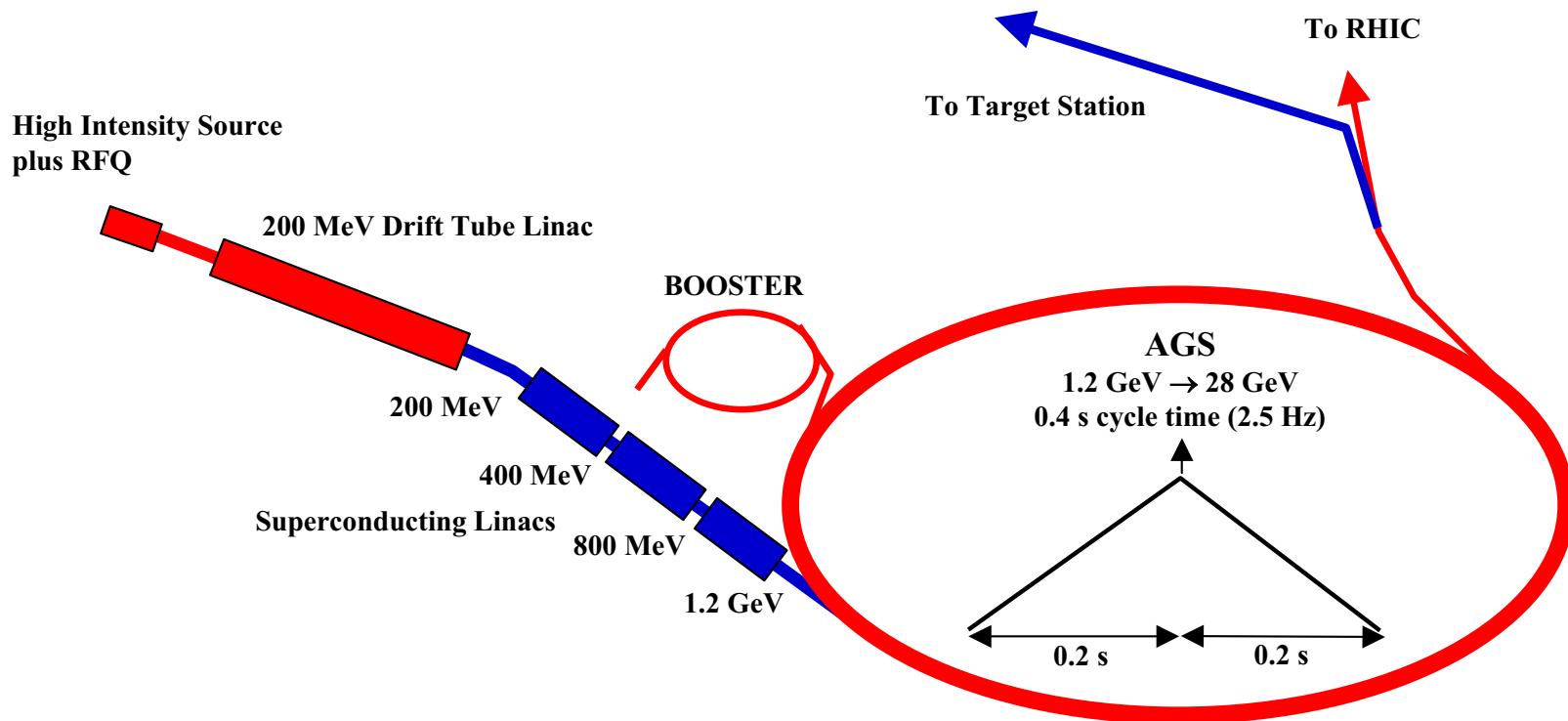
- Focus has been on BNL-Homestake = 2540km
- BNL-Henderson (2767 km) may be even better
- BNL-Soudan (1712) less so (with LAr FarDet, maybe possible)

## BNL Plan Overview

- Upgrade BNL AGS proton driver to 1 MW, don't rule out 2 MW.
- Develop target/horn system able to handle >1 MW.
- Produce on-axis wide band high-ish energy neutrino beam ( $E_{\text{T2K}} < E_{\text{BNL}} < E_{\text{NuMI}}$ ).
- Find a **500 kton fiducial mass water Cherenkov detector**,
- at a 2000 – 3000 km distance (focus is on 2500 km).
- Run for  $5 \times 10^7$  secs (over 5 years) in neutrino mode.
- Run 2 MW, 5 years in anti-neutrino mode if needed.

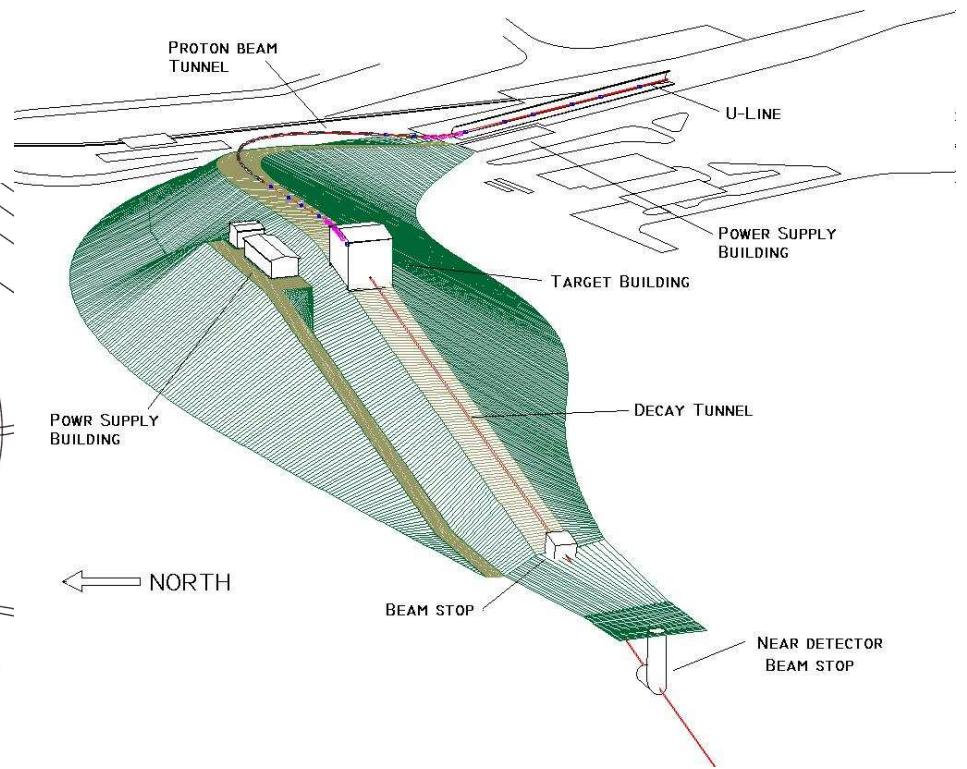
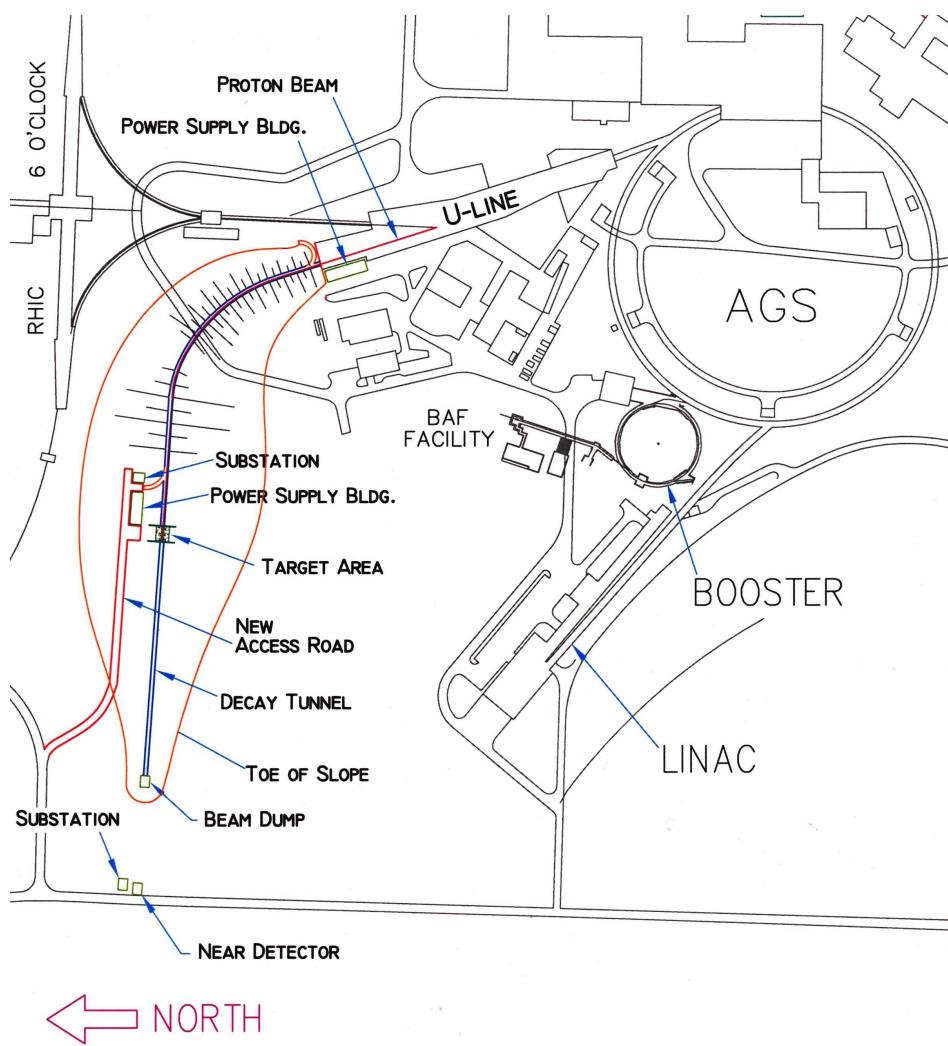
Details follow

# BNL AGS Beam Upgrades



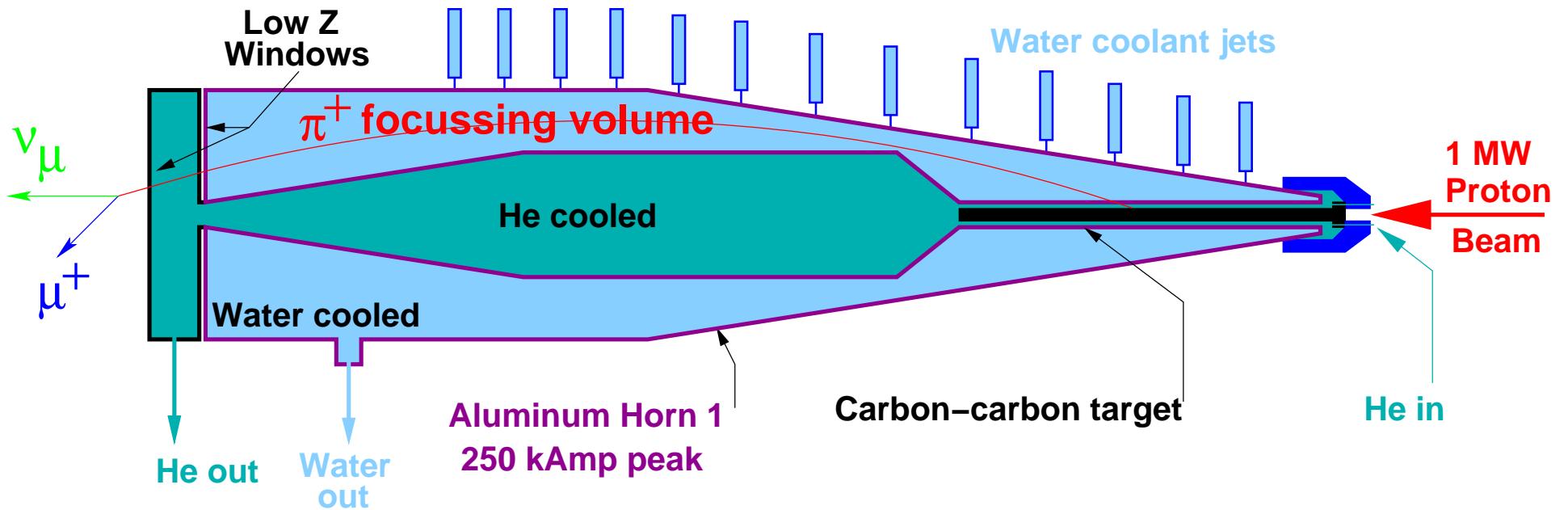
- Existing in red, upgrades in blue.
- Increase AGS cycle time to 2.5 Hz, add 1.2 GeV Superconducting LINAC.
- Upgrades are practical, no magic (ie new technology) needed.

# Beam Line and Hill



- Can point to most points west, fits on site
- Keep hadrons above the water table
- Room for a (very) near detector
- Hill cheaper than tunnel

## Target and 1st Horn



- Conventional pulsed, hadron focussing horns
- Baseline: carbon-carbon target, water + He cooling
- R&D underway with real experiments
- Collaboration with FNAL, JPARC, others

## The Detector

Assumed:

- UNO-class detector
- 500 kton fiducial mass
- Better than SuperK reconstruction

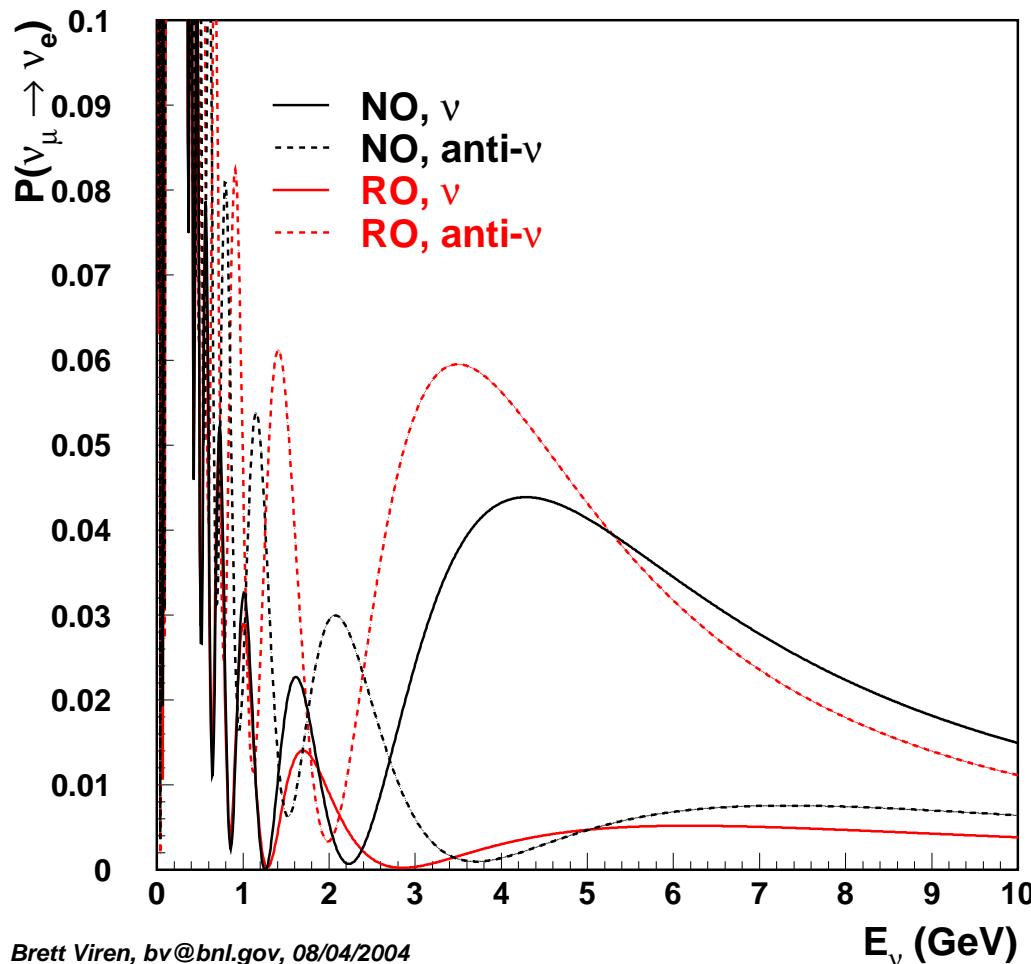
# Separating Multiple Appearance Effects

Many effects, but in different energy ranges:

energy (GeV)	$\sin^2 2\theta_{13}$	$\Delta m_{32}^2$	$\delta_{CP} =$	$\theta_{23}$
$\nu$	$> 0$	$(> 0, < 0)$	$(\frac{\pi}{4}, -\frac{\pi}{4})$	$(< \frac{\pi}{4}, > \frac{\pi}{4})$
	↑	–, –	↑, ↓	↑↑, ↓↓
	↑	–, –	↑↑, ↓↓	↓↓, ↑↑
$\bar{\nu}$	↑	↑↑, ↓↓	↑↑, ↓↓	↓↓, ↑↑
	↑	–, –	↓↓, ↑↑	↓↓, ↑↑
	↑	↓↓, ↑↑	↓↓, ↑↑	↓↓, ↑↑

# Mass Hierarchy effects

## Mass hierarchy



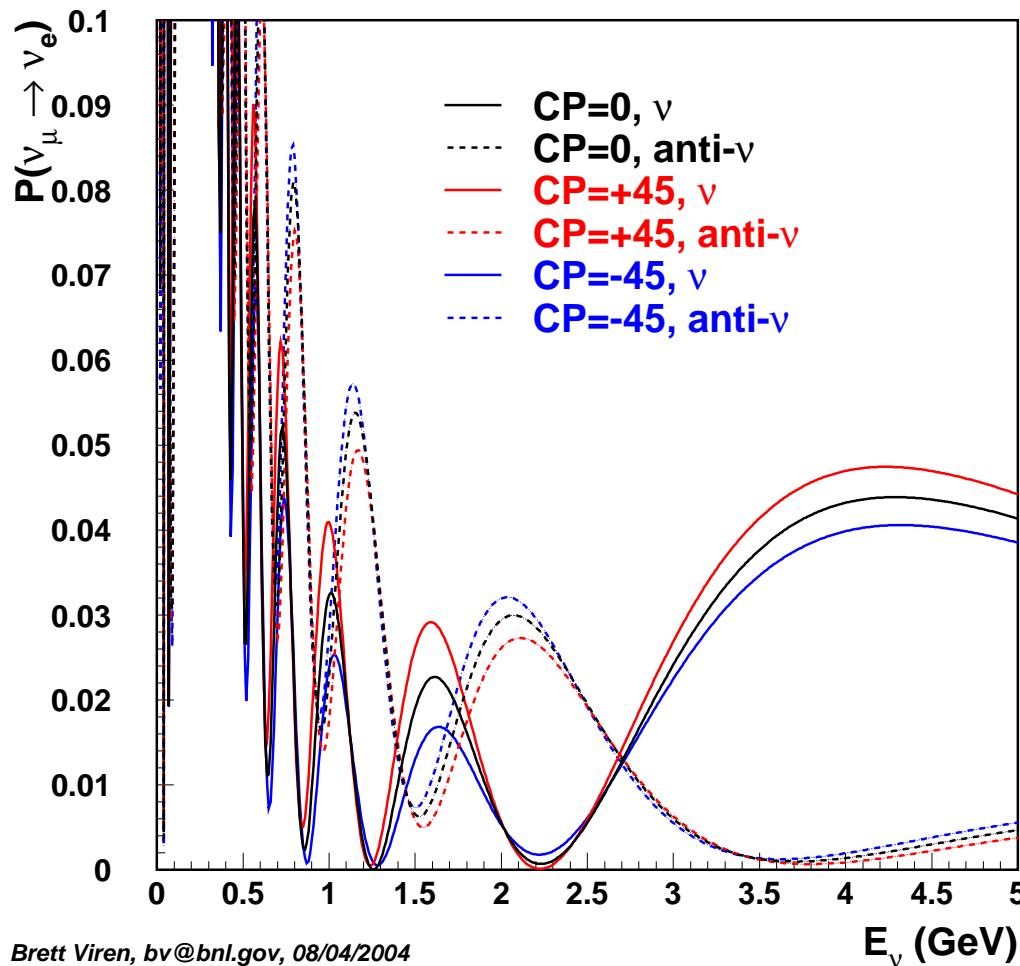
$\text{sign}(\Delta m_{32}^2) = ??.$

Matter effects at 1st oscillation:

- $\nu$ :  
 $\Delta m_{32}^2 > 0 \Rightarrow$  enhancement,  
 $\Delta m_{32}^2 < 0 \Rightarrow$  suppression
- $\bar{\nu}$ :  
 $\Delta m_{32}^2 > 0 \Rightarrow$  suppression,  
 $\Delta m_{32}^2 < 0 \Rightarrow$  enhancement

# CP phase effects

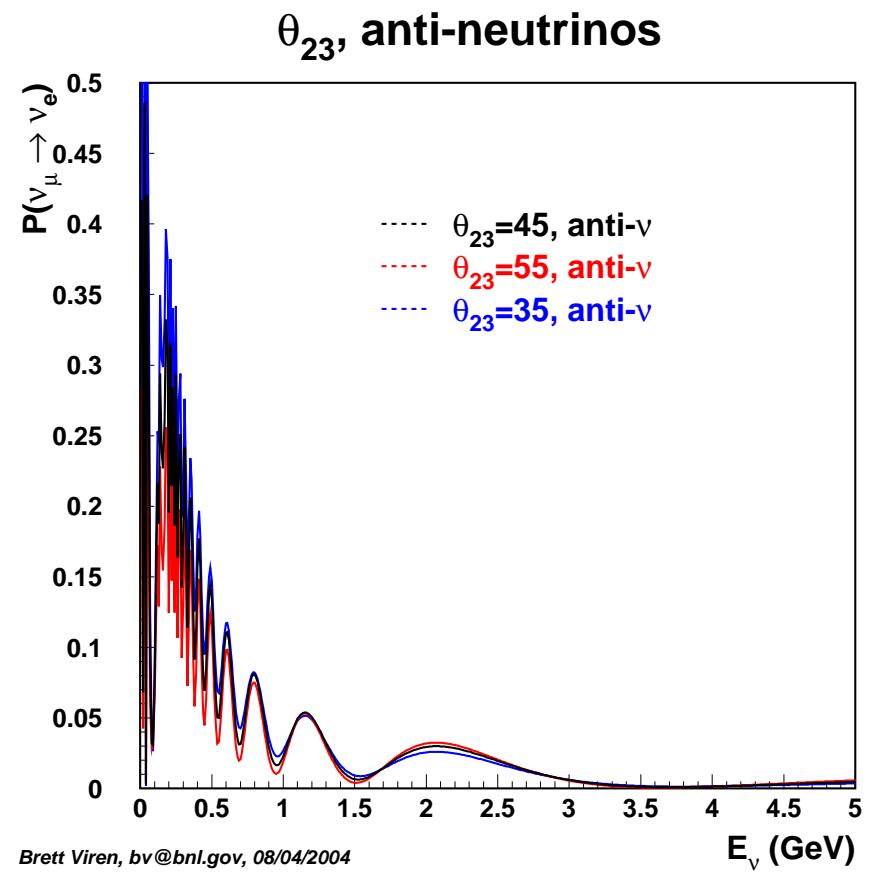
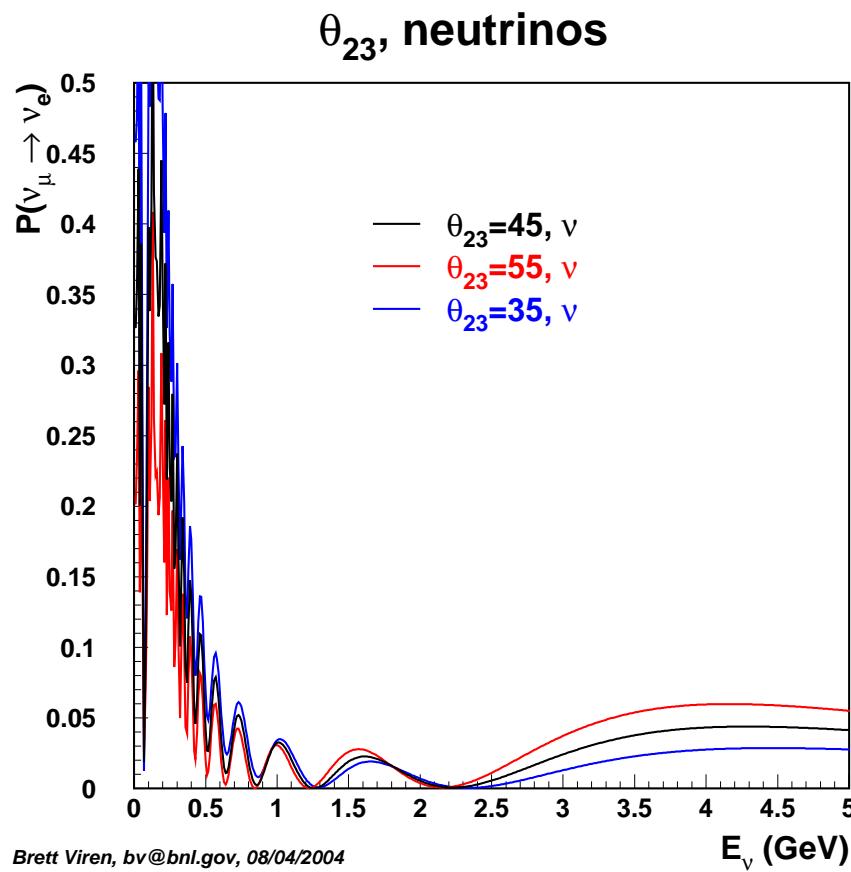
## CP phase



At mid energies:

- $\nu$ :  
 $\delta_{cp} > 0 \Rightarrow$  enhancement,  
 $\delta_{cp} < 0 \Rightarrow$  suppression
- $\bar{\nu}$ :  
 $\delta_{cp} > 0 \Rightarrow$  suppression,  
 $\delta_{cp} < 0 \Rightarrow$  enhancement

# $\theta_{23}$ effects



Effect for both  $\nu$  and  $\bar{\nu}$  at low energies.

## Current Analysis

**Disappearance** related analysis “easy”. The effects are so large.

**Appearance**, less so. Two scenarios:

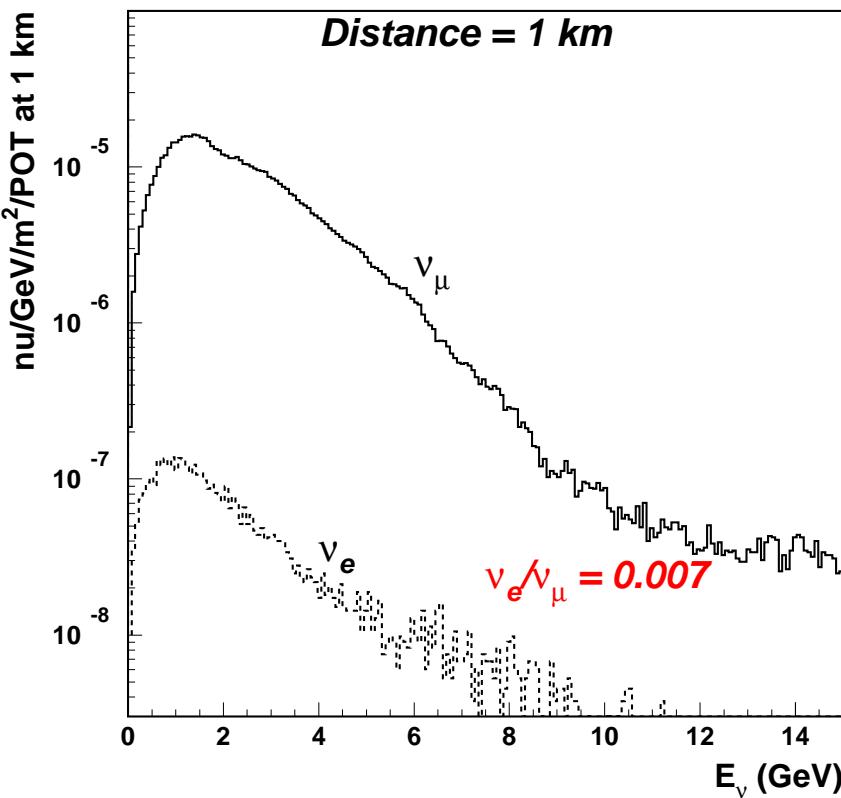
1. Succeed in achieving strong background rejection by improving the water Cherenkov technology beyond SuperK  
⇒Run wide-band on-axis beam.
2. Fail and suffer with weak background rejection in water Cherenkov  
⇒Run off-axis beam.
  - Reduces NC feed down by reducing high energy  $\nu$ s
  - Still retain enough spectral width to resolve multiple oscillations

Both currently assume: beam power of 1 MW  $\nu$  (2 MW  $\bar{\nu}$ ) running,  $5 \times 10^7$  seconds run time, 500 kton water Cherenkov detector at 2540 km.

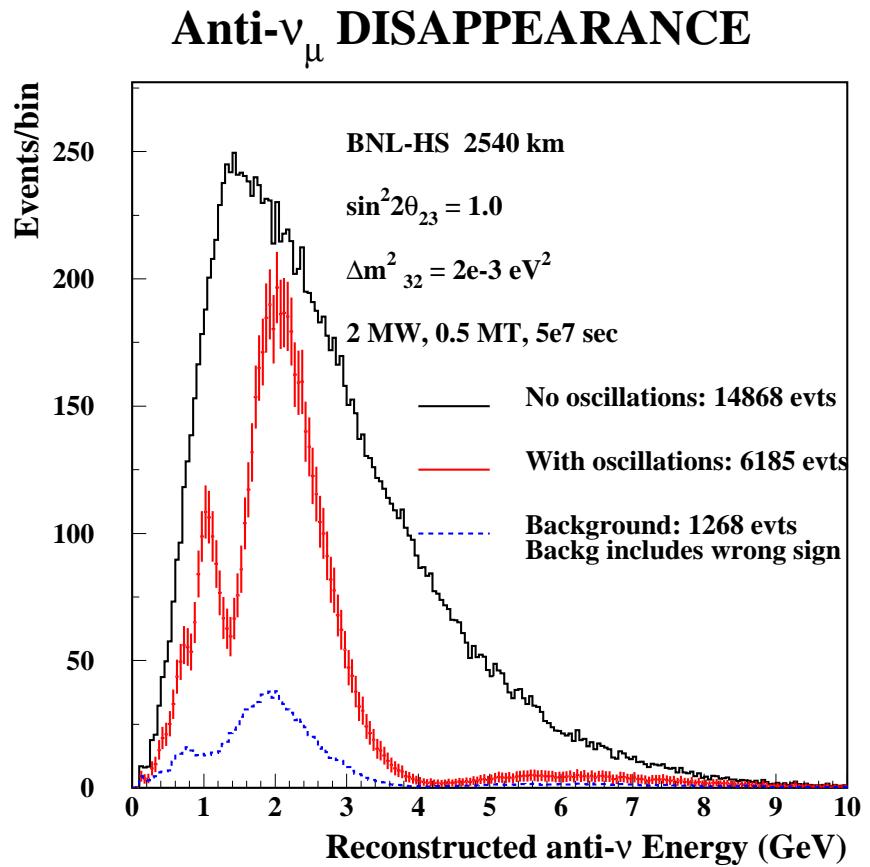
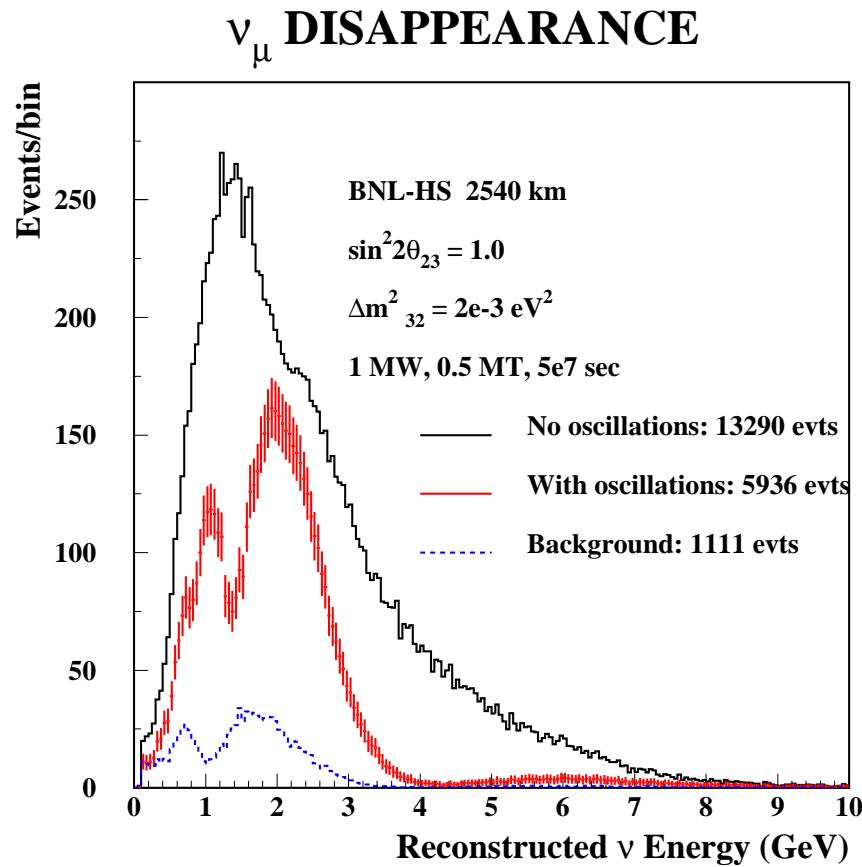
(Plots shown are from M.Diwan, BNL/UCLA/APS workshop 3/04)

# Scenario 1: BNL On-Axis Beam Flux

**BNL Wide Band. Proton Energy = 28 GeV**



- Flux and contamination experimentally known
- 60 cm graphite target.
- 4 m diameter, 200 m long tunnel
- $5 \times 10^{-5} \nu/\text{m}^2/\text{POT}$  @ 1 km.
- 52000 CC, 17000 NC events  
(1MW, 2540 km, 0.5 MT,  $5 \times 10^7$  sec)

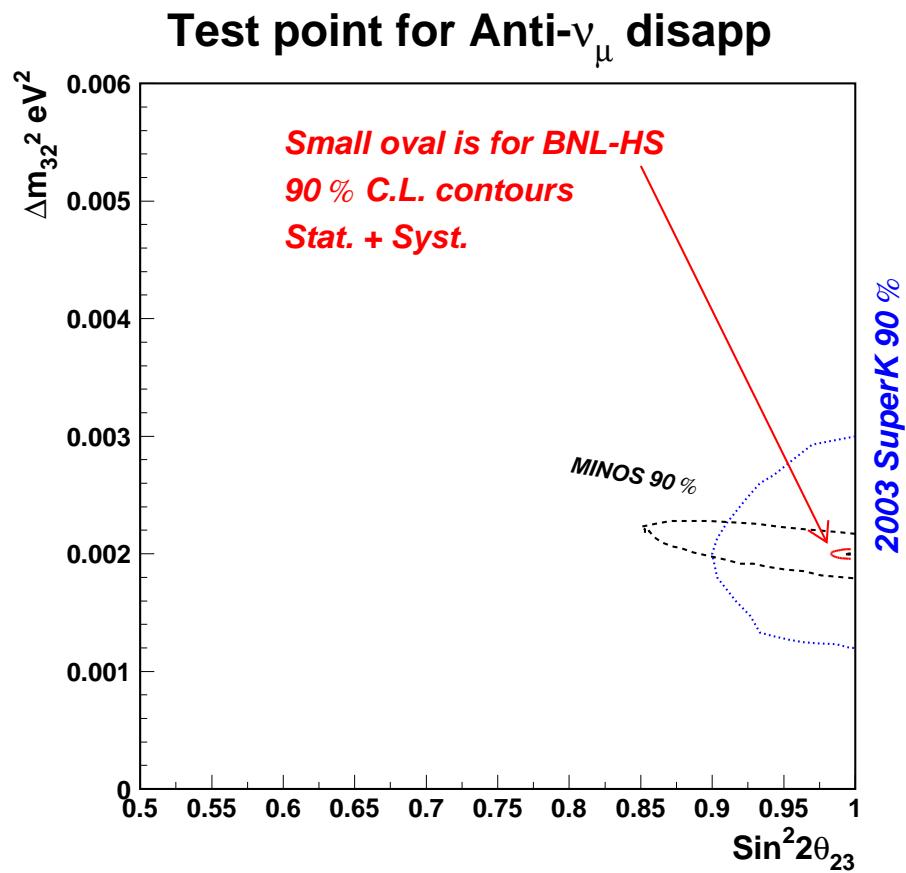
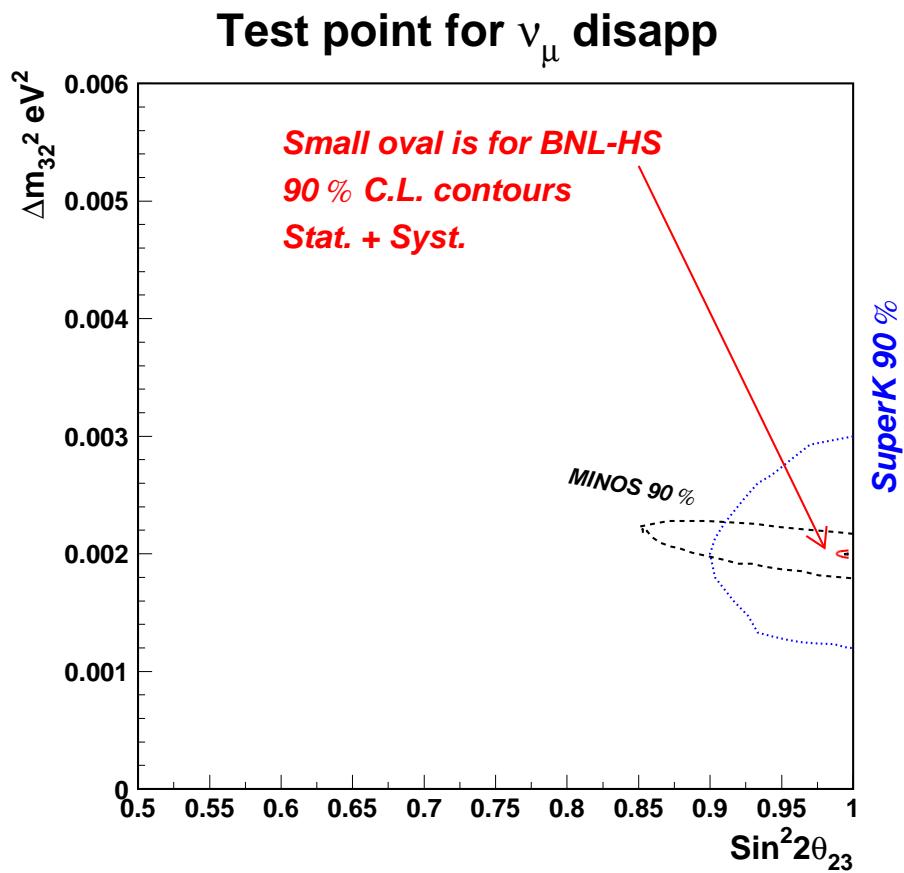


Node pattern provides high  $\Delta m^2_{32}$  resolution.

Energy calibration is very important.

Flux normalization not important for measurement of  $\sin^2 2\theta_{23}$

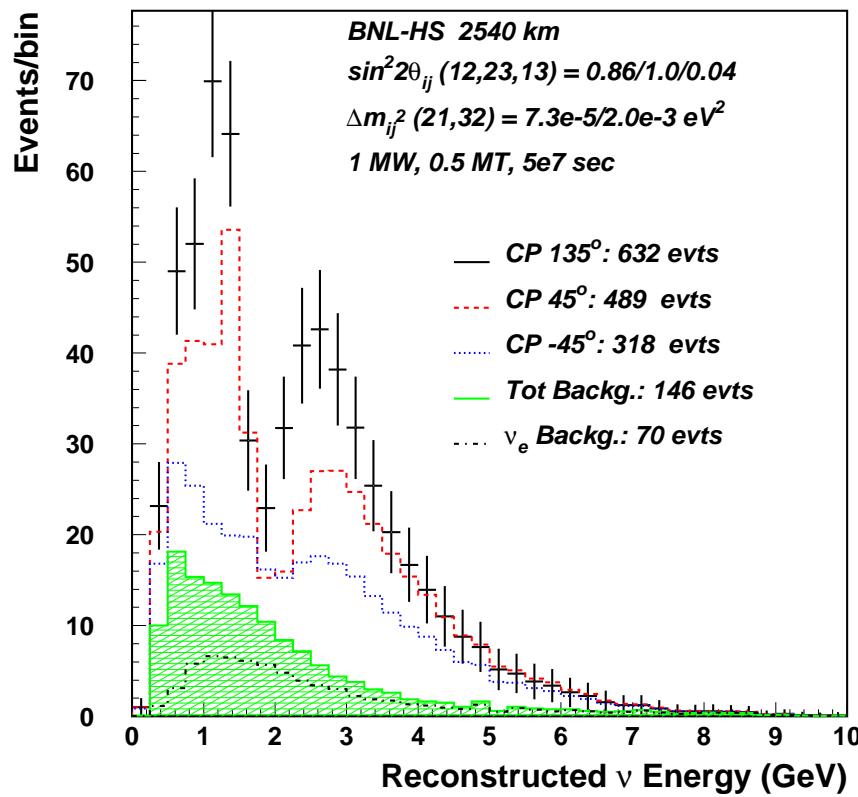
# Disappearance resolution, measurement of $\theta_{23}$ , $\Delta m_{32}^2$



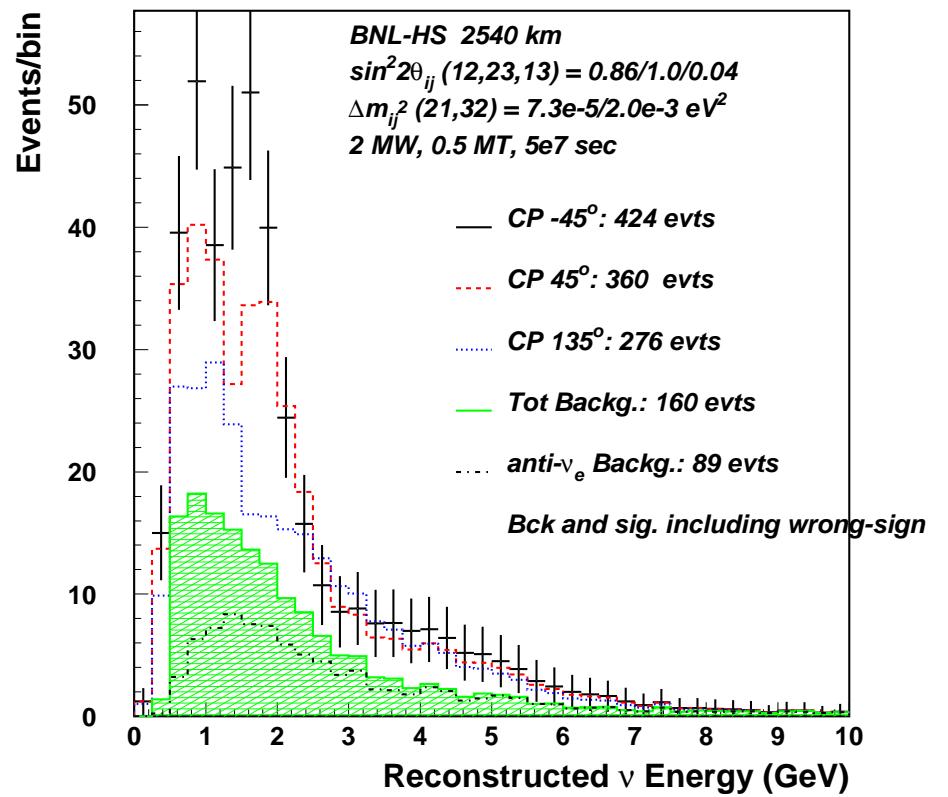
$\sim 1\%$  resol. on  $\Delta m_{32}^2$  and  $\sin^2 2\theta_{23}$  over broad range if we can understand detector energy scale to 1%. Robust against other systematics.

# Appearance, Normal Hierarchy

## $\nu_e$ APPEARANCE

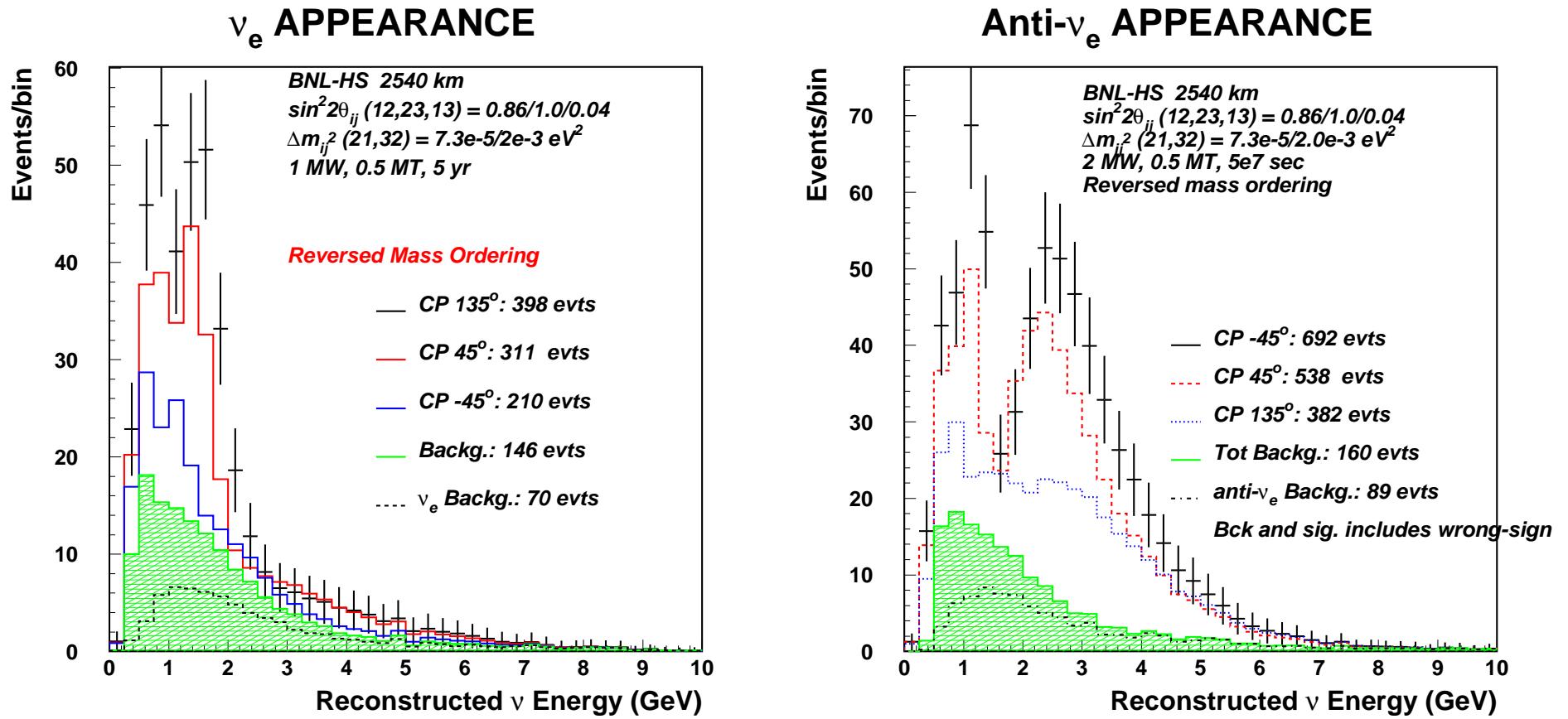


## Anti- $\nu_e$ APPEARANCE



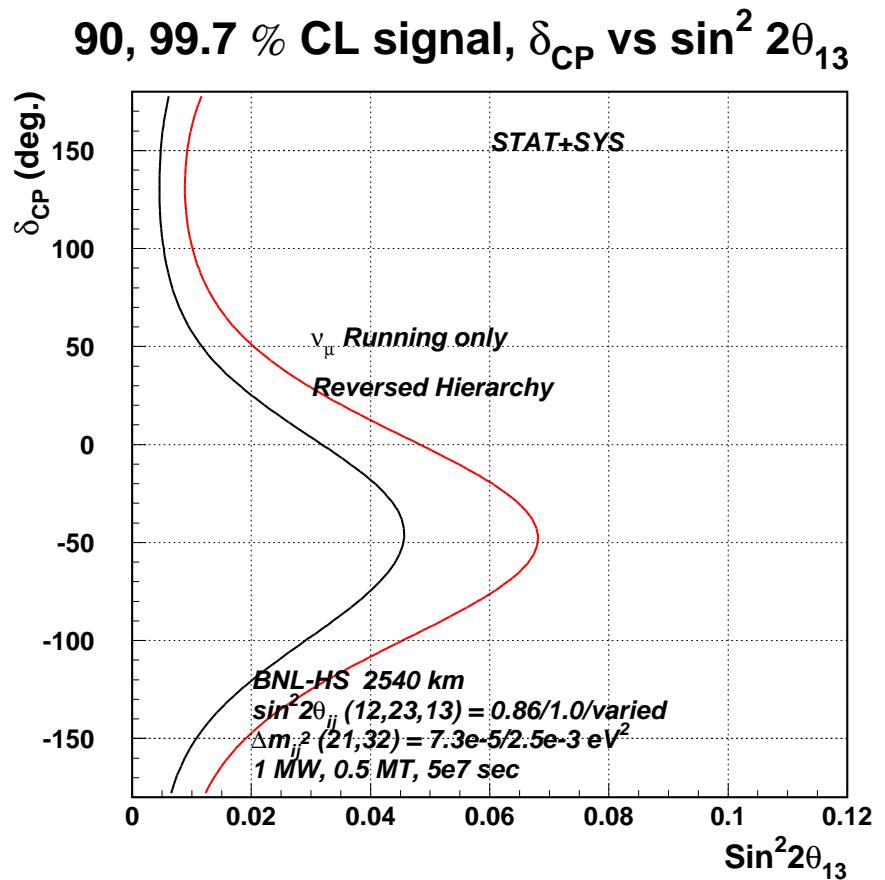
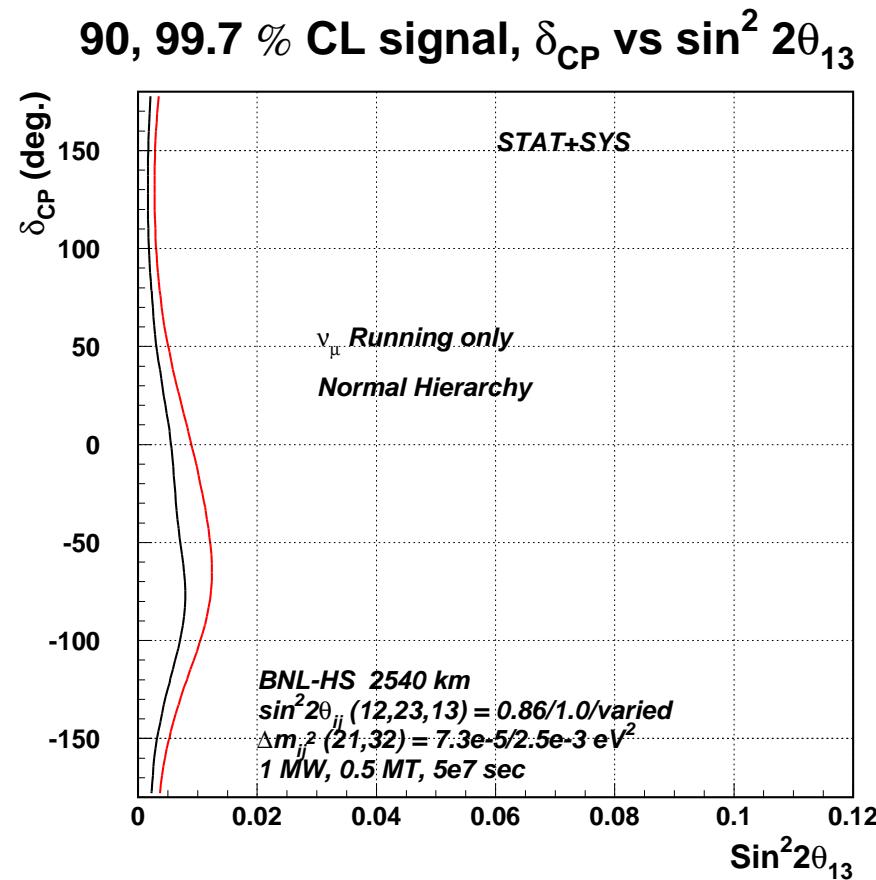
$\Delta m_{32}^2 = 0.002 \text{ eV}^2$ ,  $\sin^2 2\theta_{13} = 0.04$ . Matter effects included.

# Appearance, Reversed Hierarchy



$\Delta m_{32}^2 = -0.002 \text{eV}^2$ ,  $\sin^2 2\theta_{13} = 0.04$ . Matter effects included.

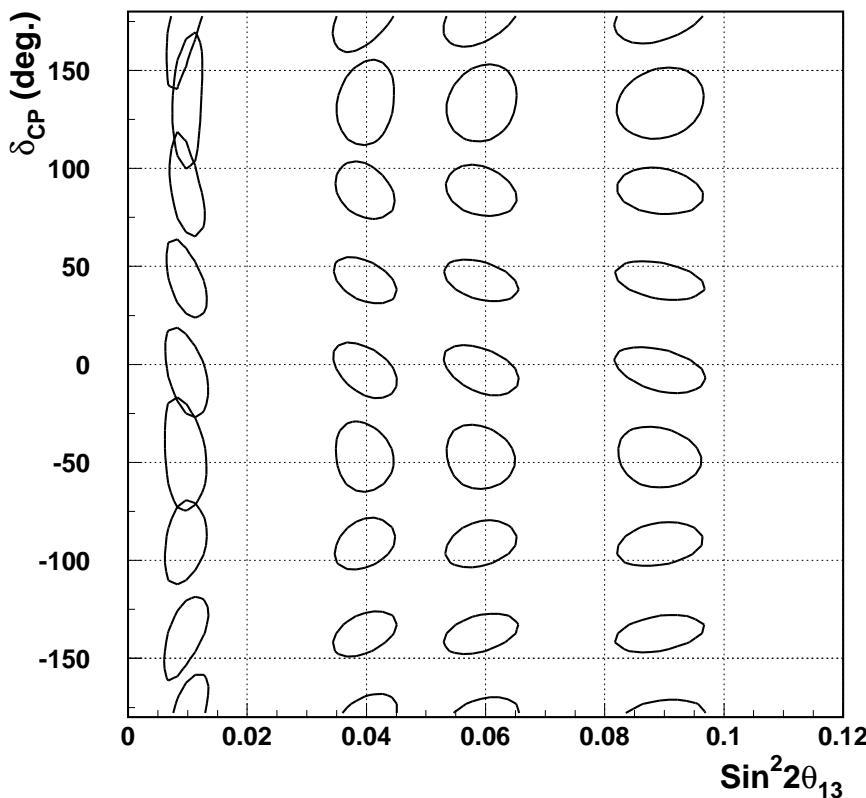
# $\sin^2 2\theta_{13}$ sensitivity



If reversed hierarchy and in the unlucky region, need to run anti-neutrinos.

# CP measurement after nu and anti-nu

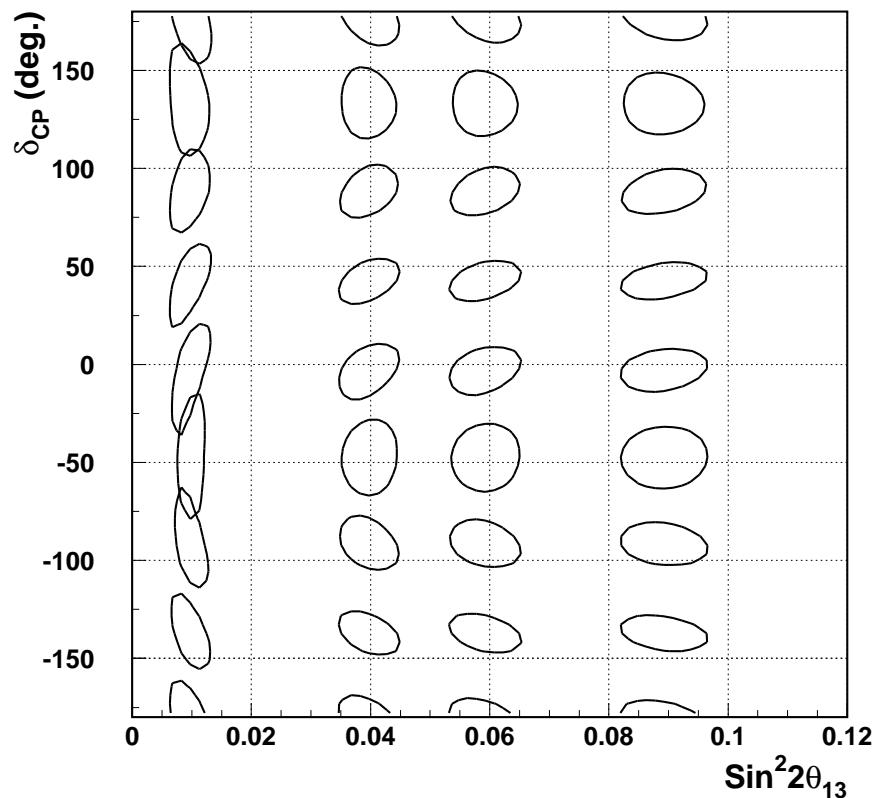
**Regular hierarchy νν and Antivνν running**



Left: Regular mass hierarchy

No  $\delta_{CP} / \sin^2 2\theta_{13}$  degeneracy, only the  $\theta_{23}$  ambiguity is left.

**Reversed hierarchy νν and Antivνν running**



Right: reversed mass hierarchy.

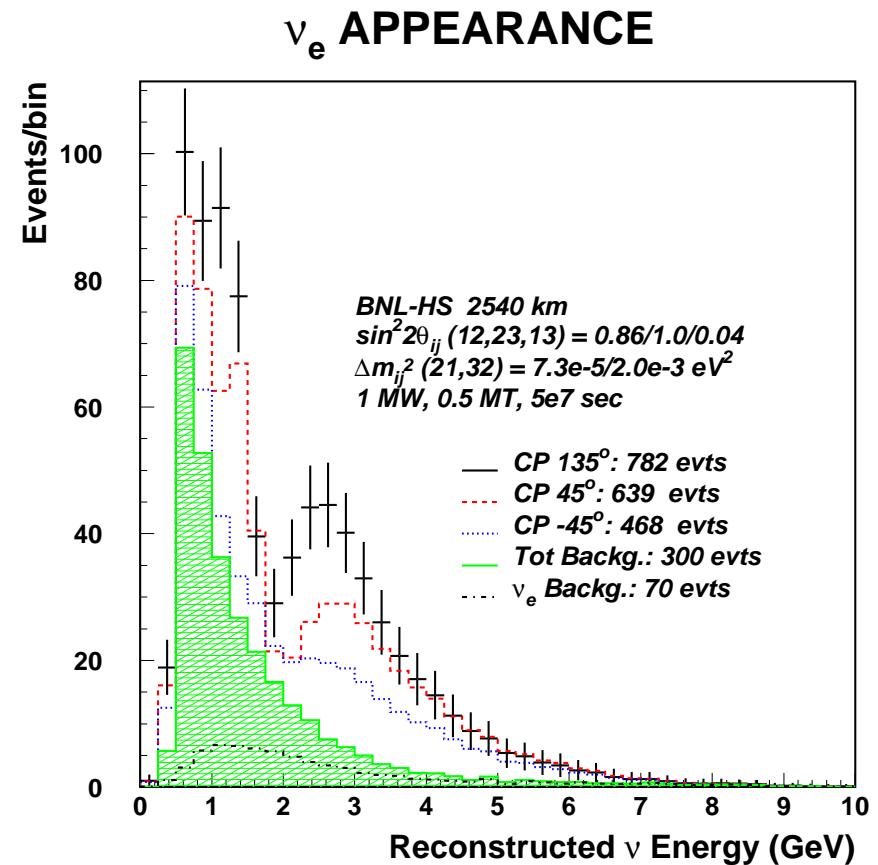
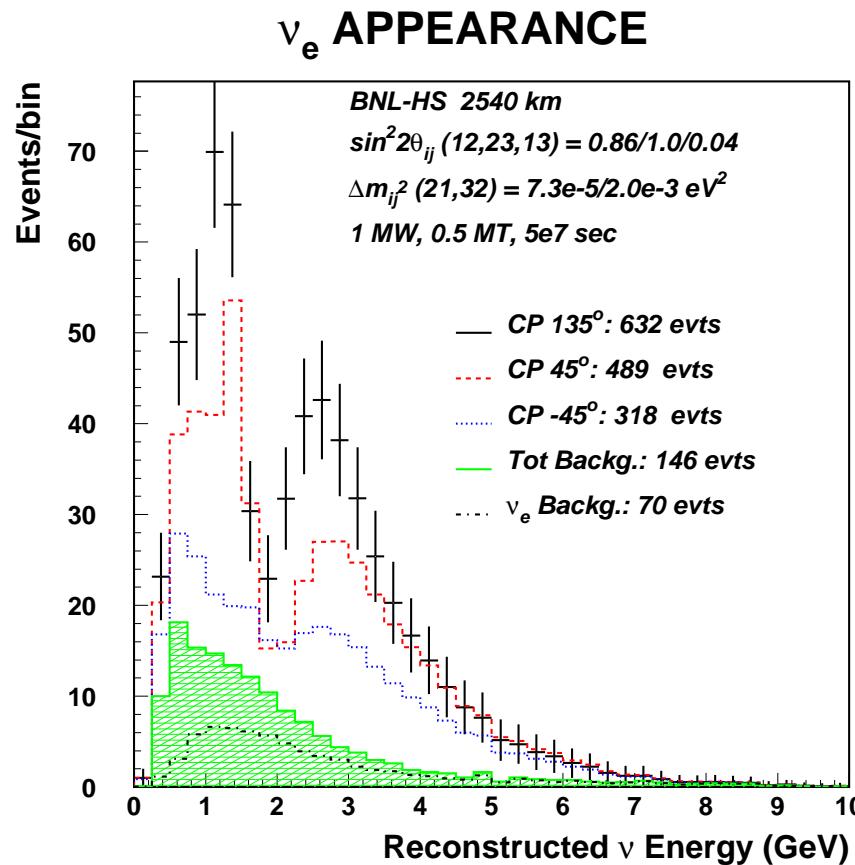
## Scenario 2. the background beats us down

Same running conditions.

Particles within 20 deg. separation cannot be resolved.

- Some effect on disappearance.
- Some effect on appearance with  $E > 2.5GeV$ .
- Large effect at lower energies.

# Worse background spectra

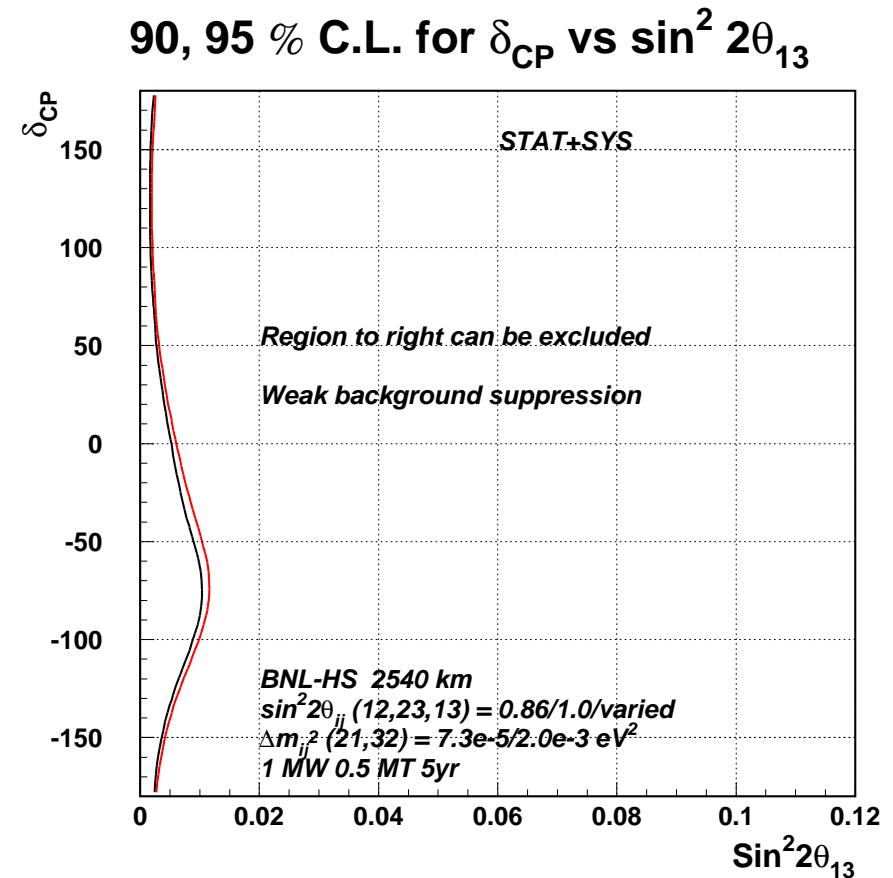
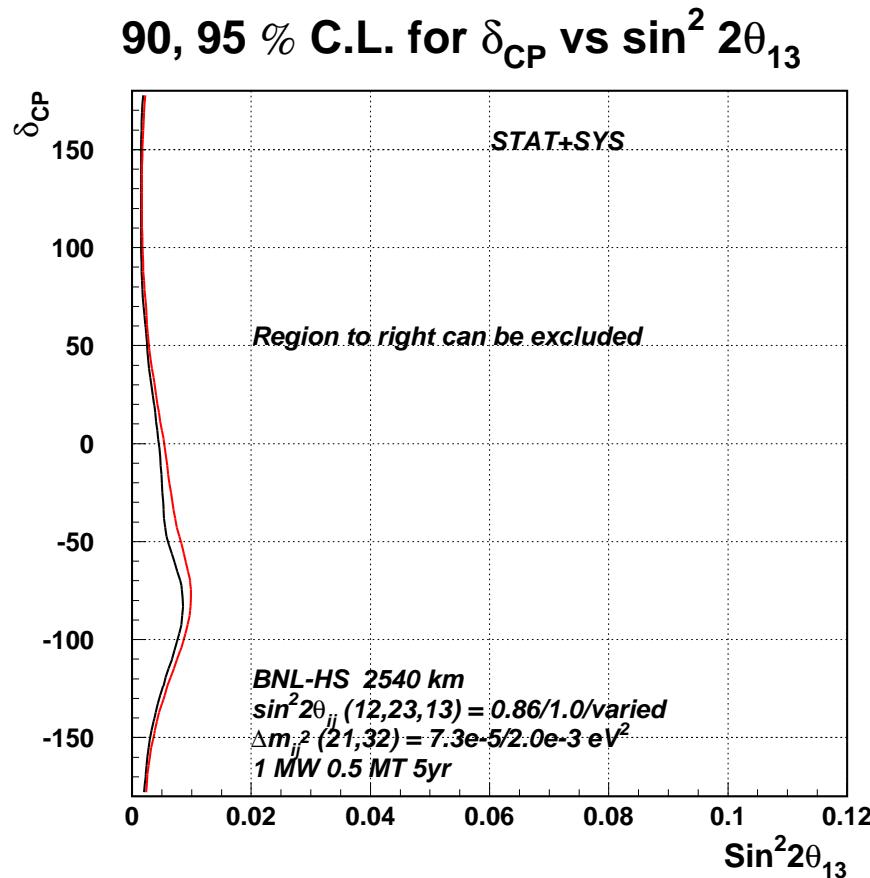


Left: strong rejection

Right: weak rejection

Background is confined to lower node.

# Worse background limit



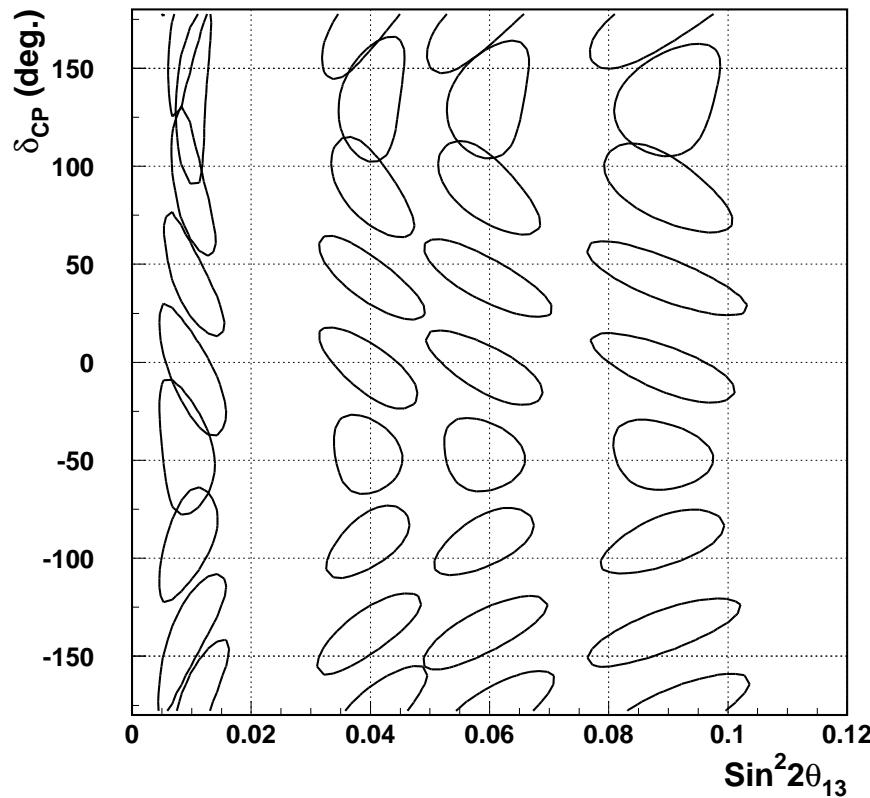
Left: strong rejection

Right: weak rejection

Limit affected by  $< 2\times$ . Using knowledge of  $\delta m_{32}^2$  in extracting limit.

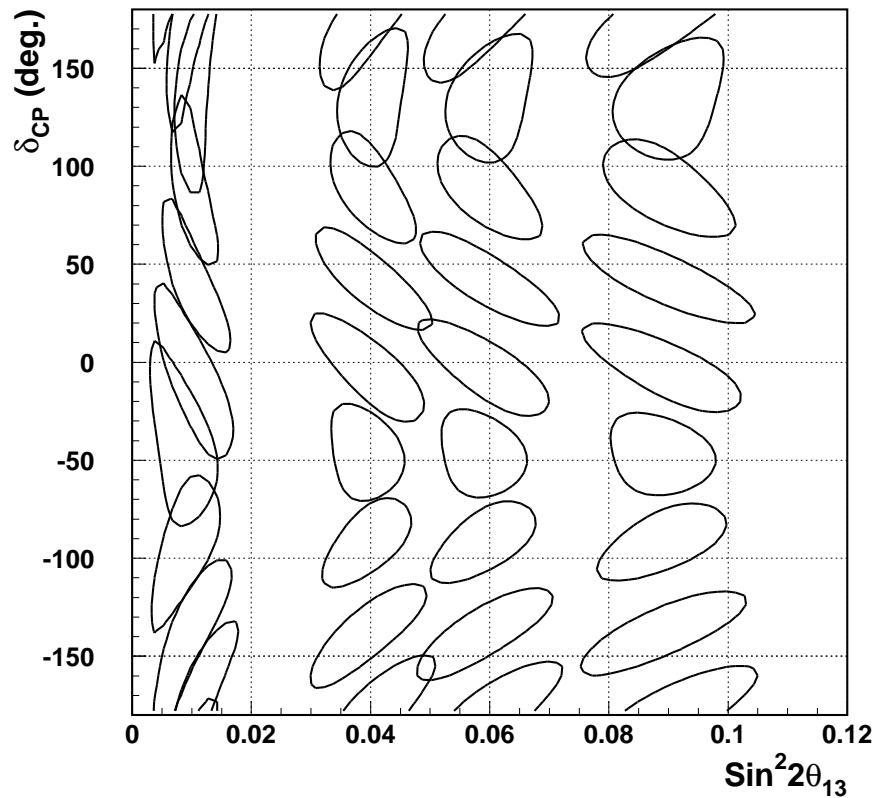
# Worse background CP-measurement

**Resolution  $\delta_{CP}$  vs  $\sin^2 2\theta_{13}$**



Left: strong rejection

**Resolution  $\delta_{CP}$  vs  $\sin^2 2\theta_{13}$**



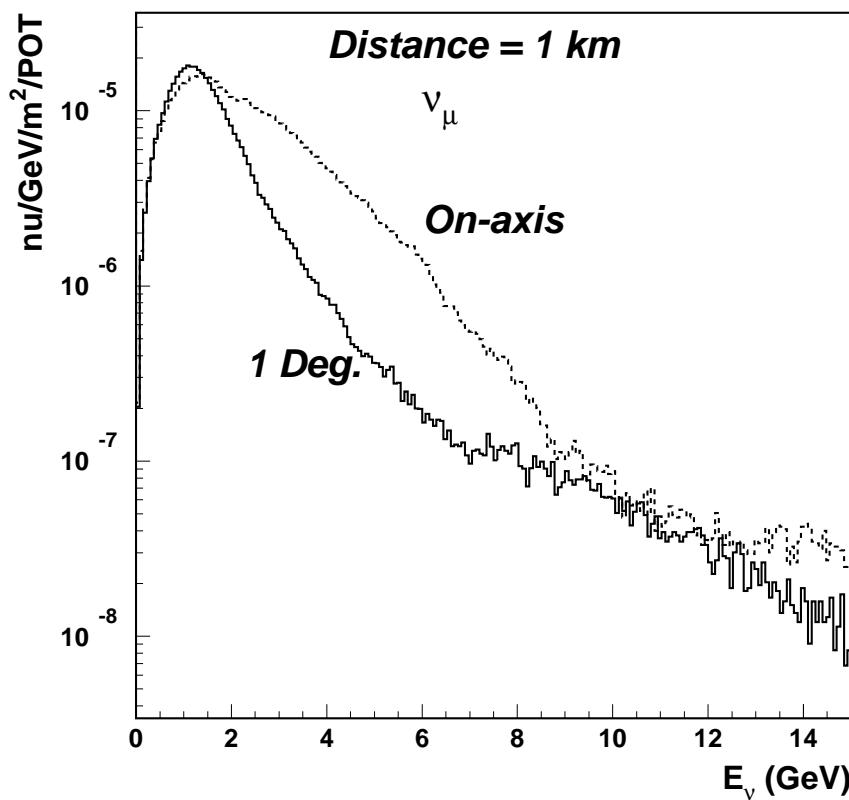
Right: weak rejection

Worse background:  $\delta_{CP}$  worse by  $\sim 50\%$

Could one run off-axis to do better? →

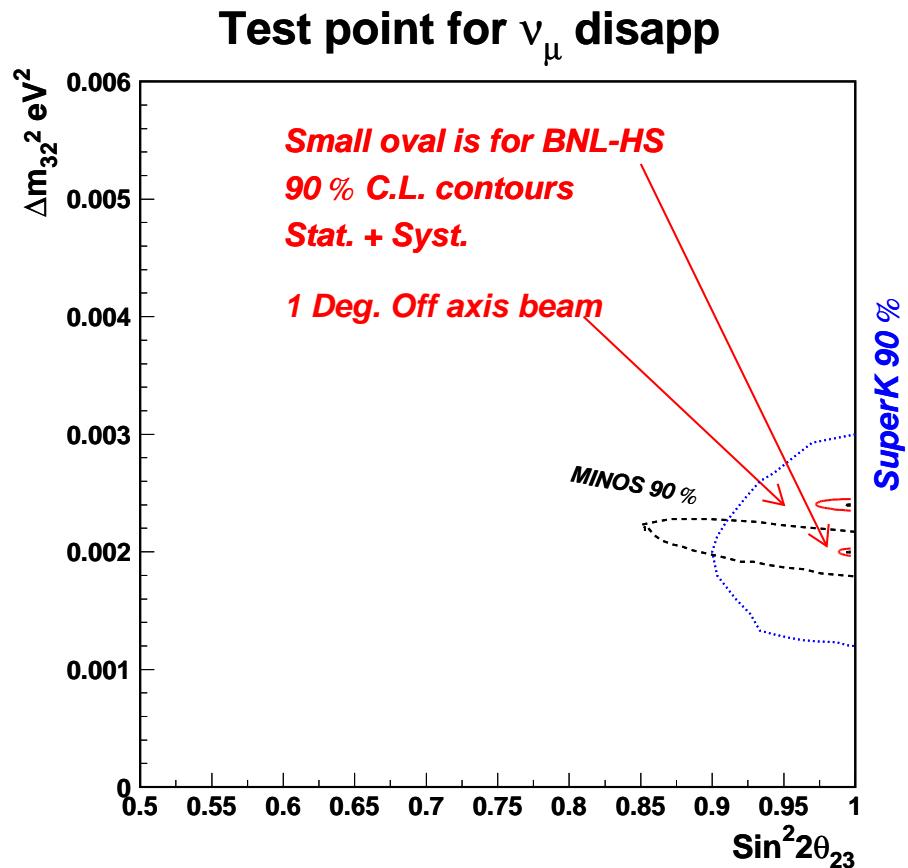
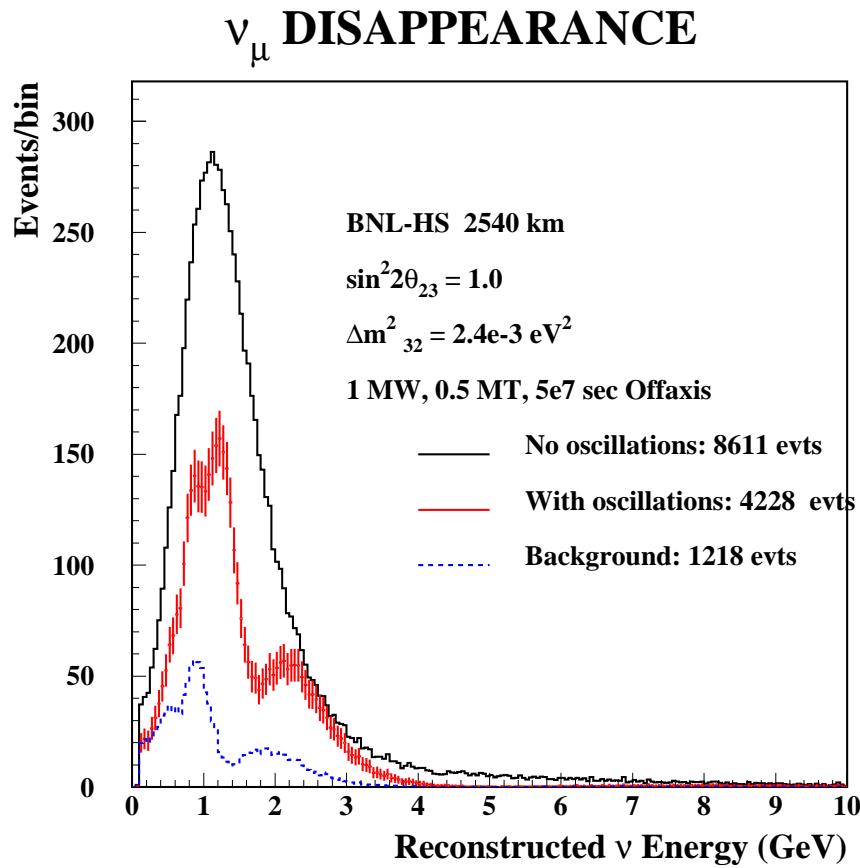
# 1 deg. Off axis beam

**BNL Proton Energy = 28 GeV**



- Move target and horn by 1.3 m and rotate 1 deg.
- Same 4 m diameter, 200 m long tunnel
- Will need large beam dump
- 19000 CC, 7000 NC events (1MW, 2540 km, 0.5 MT,  $5 \times 10^7$  sec)

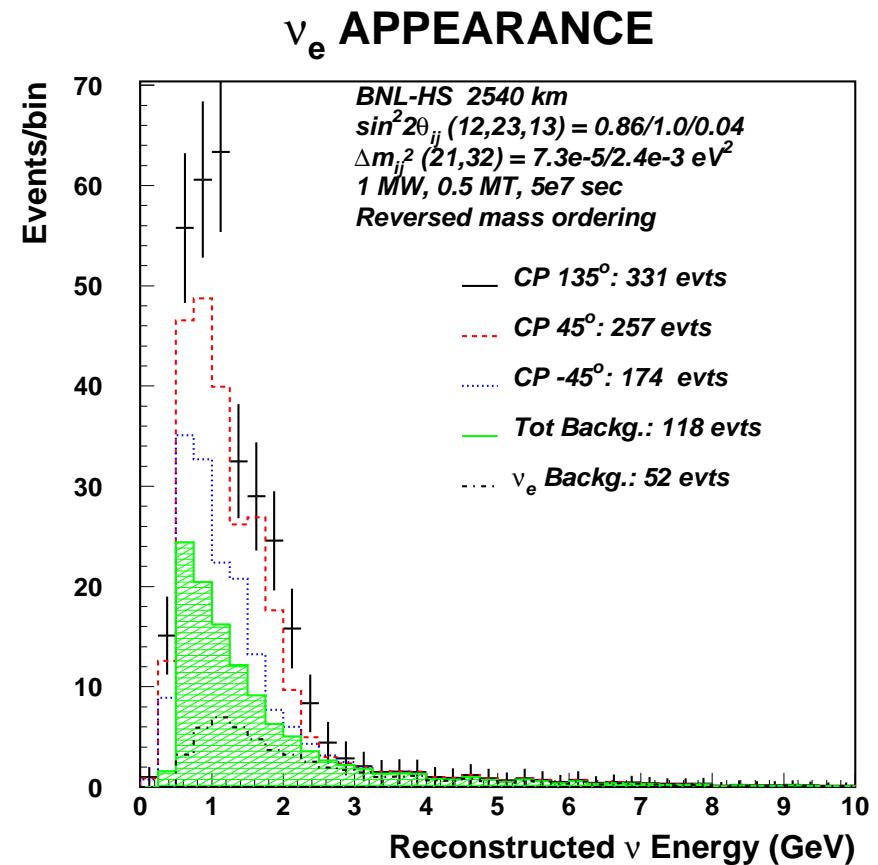
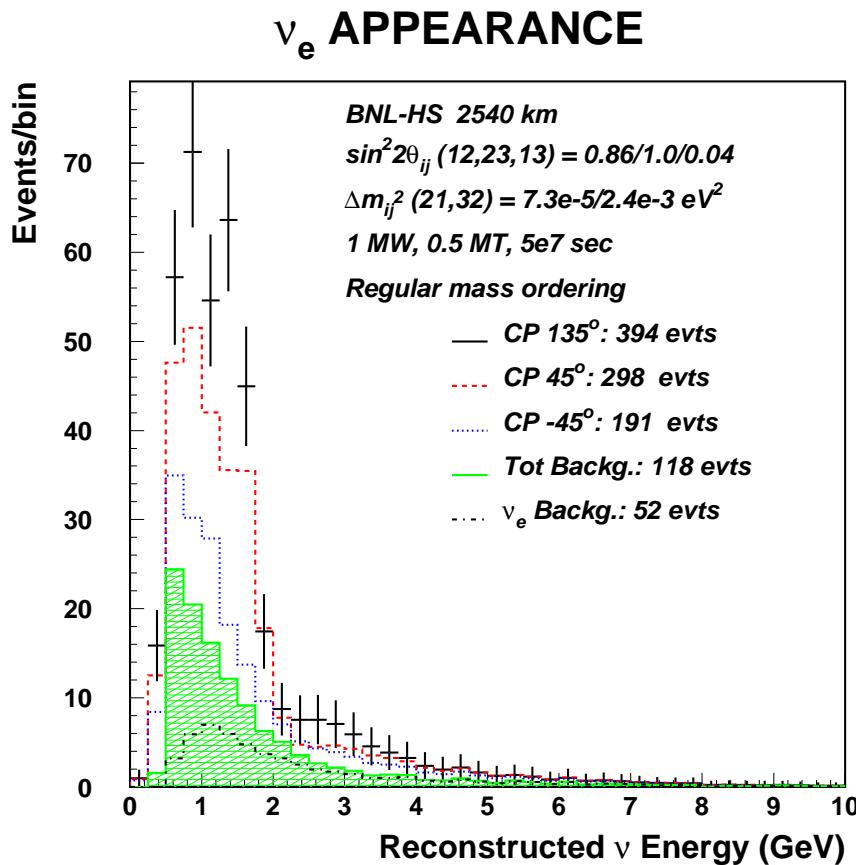
# Disappearance with $1^\circ$ Off-Axis Beam



Lose one node, Resolution of  $\sin^2 2\theta_{23}$  is reduced.

About factor of 3 worse compared to wide-band running.

# Appearance with 1° Off-Axis Beam

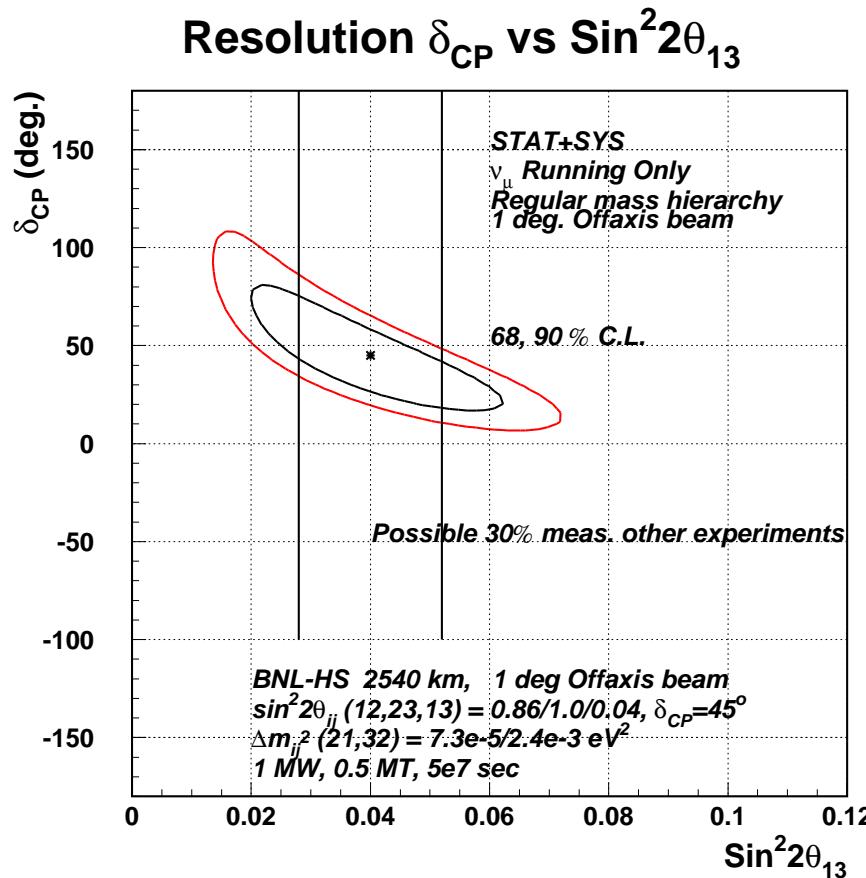


Left: normal mass hierarchy

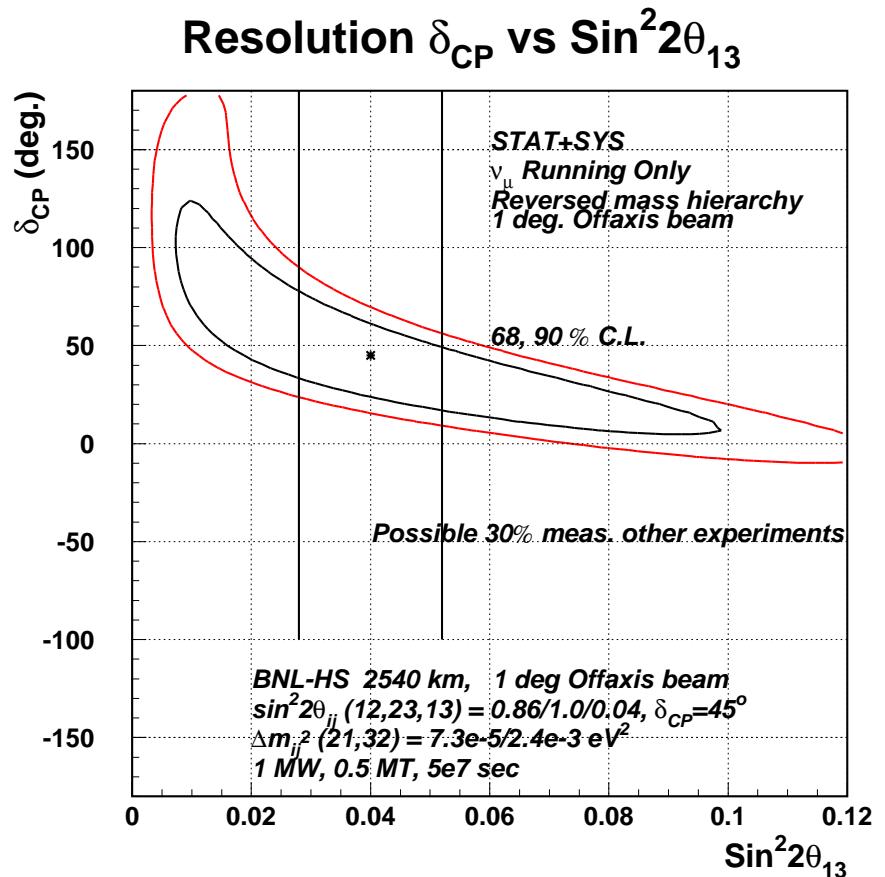
Right: reversed mass hierarchy

With weak background rejection reduce NC background by  $\sim 3.5 \times$  with 1° beam. Mass ordering discrimination worse.

# Measuring $\delta_{CP}$ with 1° Off-Axis Beam



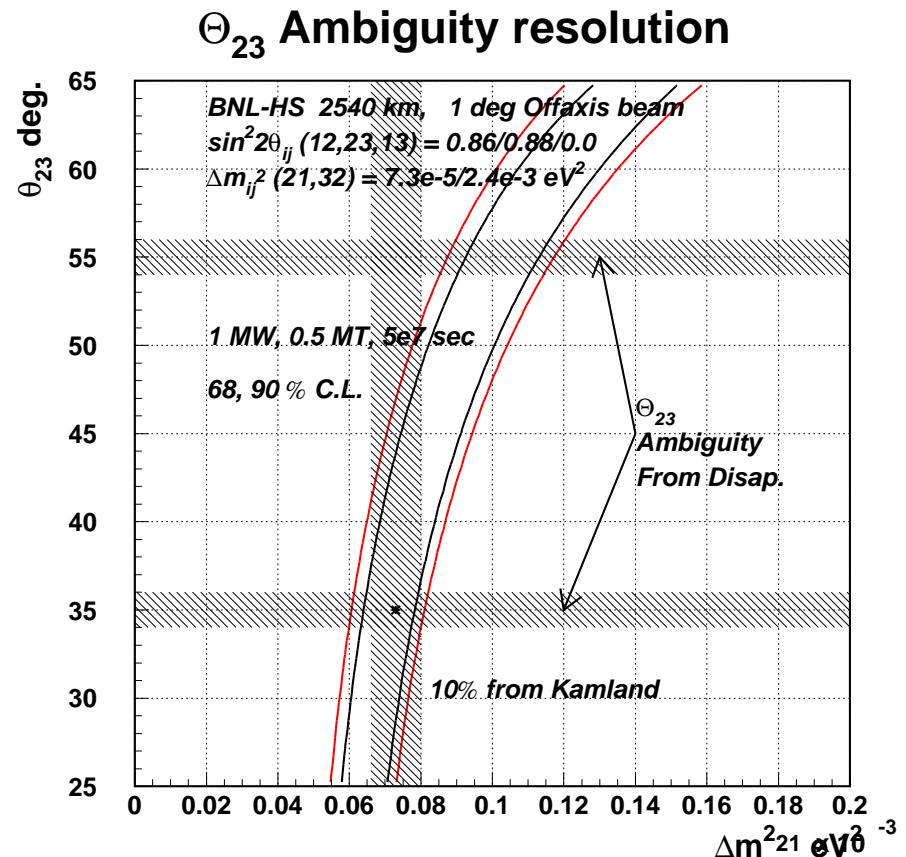
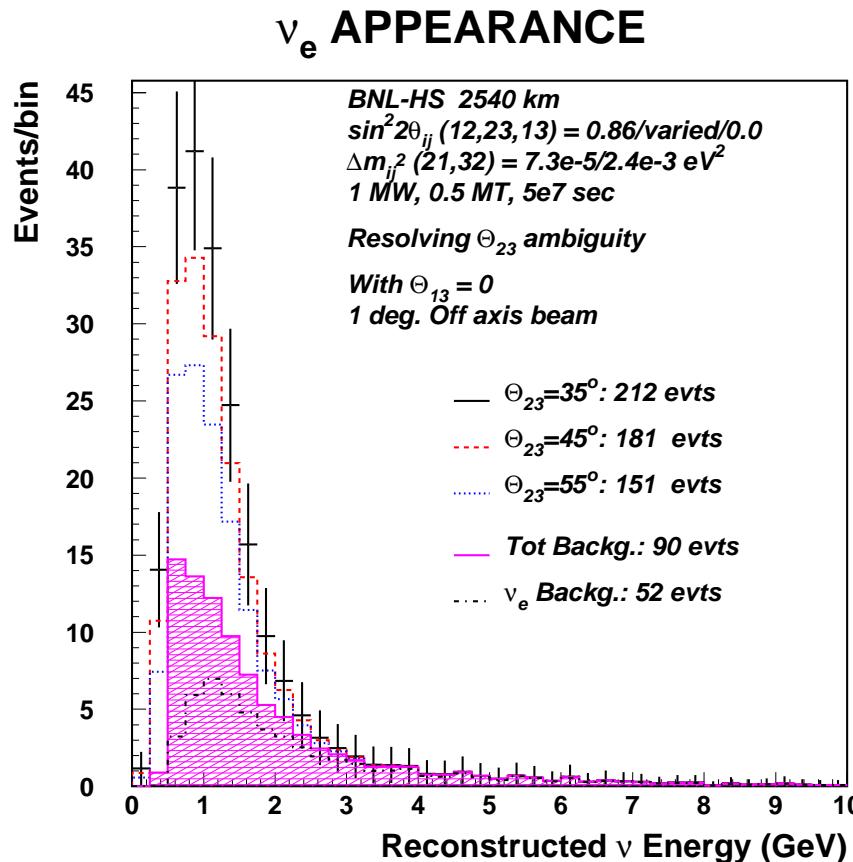
Left: normal mass hierarchy  
Large CP vs.  $\sin^2 2\theta_{13}$  correlation. Needs separate measurement of  $\sin^2 2\theta_{13}$ .



Right: reversed mass hierarchy

# Break $\theta_{23}$ Degeneracy if Non-Maximal Mixing

Asside: with strong background rejection **and** off-axis beam **and** help from KamLAND (for  $\delta m_{21}^2$ ), can measure  $\theta_{23}$  (not just  $\sin^2 2\theta_{23}$ ), thus breaking  $\theta_{23} \rightarrow \pi/2 - \theta_{23}$  ambiguity.



## Analysis Summary

- Disappearance results are glaring and robust against different scenarios.
- To reach design sensitivity for appearance results, improvements in water Cherenkov technology in order to reduce  $\nu_e$  background below 2 GeV is required.
- More background can be tolerated by switching to  $1^\circ$  off-axis beam. Some reduction in sensitivity would be suffered.
- With strong background suppression and the  $1^\circ$  off-axis beam the  $\theta_{23}$  ambiguity can be resolved if the atmospheric- $\nu$  sector found to be non-maximally mixed.

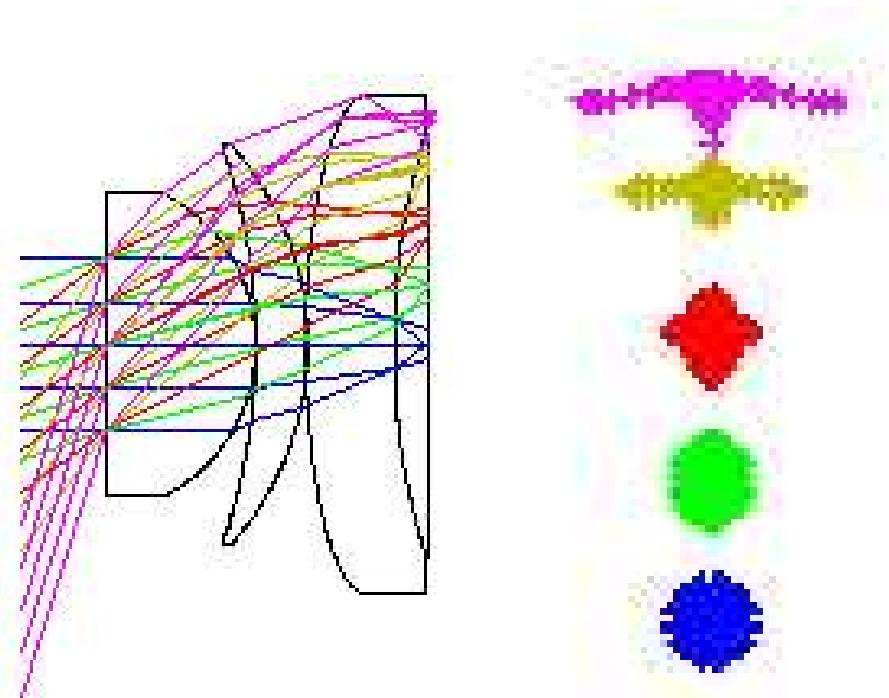
## Confronting the $\nu_e$ Background Problem

Software improvements on standard SK reconstruction (Yanagisawa, next talk)  
Focusing photo-detectors reconstruct Cherenkov photons' direction (and the usual time, PE). Considering:

Takacs's Lens:

- Lens designed by Peter Takacs of BNL coupled with HPD readout →
- Potential: array of ReFerence tubes (see Sat. talk)

Work is underway to incorporate these into the UNO MC in order to develop and test novel reconstruction methods.



$\pm 72^\circ$  angular acceptance.  
16x16 pixels  $\Rightarrow 9^\circ$  bins

## Conclusions

- The BNL VLBL neutrino beam coupled with an UNO-like far detector beyond 2000 km is a uniquely novel approach and will provide a wealth of physics results.
- The necessary upgrades to the AGS are well understood and practical. There is an active program of R&D pursuing target issues.
- Current inadequacies in water Cherenkov  $\nu_e$  background rejection need to be addressed.
  - Potential improvements by using new photodetector technology.
  - Reconstruction software improvements.
  - Off-axis running scenario as worse case.

## BNL VLBL Study Update

## On-Axis Event Counts

1 (2) MW  $\nu$  ( $\bar{\nu}$ ), 500 kT, L=2540km,  $5 \times 10^7$  sec

Assumed Strong Background Rejection.

CC $\nu_\mu N \rightarrow \mu^- X$	51800 (30050)	NC $\nu_\mu N \rightarrow \nu_\mu X$	18323 (11540)
CC $\nu_e N \rightarrow e^- X$	380 (106)		
QE $\nu_\mu n \rightarrow \mu^- p$	11767 (11868)	NC elastic	4575 (3882)
QE $\nu_e n \rightarrow e^- p$	84 (80)		
CC Single $\pi$	22053 (11872)	NC Single $\pi$	7741 (5074)
CC Two $\pi$	10143 (3336)	NC Two $\pi$	3557 (1630)
CC $> 2 \pi$	4882 (500)	NC $> 2 \pi$	1729 (560)
CC $\nu_\tau N \rightarrow \tau^- X$	$\sim 110$ (40)	(depends on $\Delta m^2$ )	

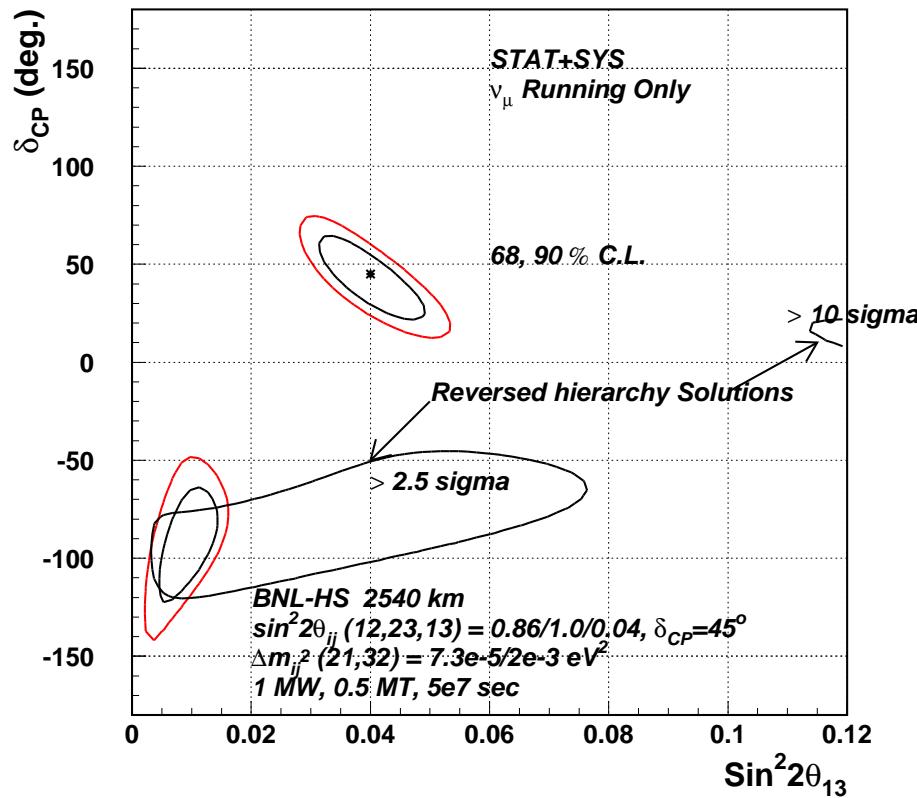
## Off-Axis Event Counts, $\nu$ -running

1 MW, 500 kT,  $\nu$ -running,  $5 \times 10^7$  sec, 2540 km

	On axis	1 Deg. Off axis
CC/NC $\nu_\mu N \rightarrow lX$	51800/18323	18931/7081
CC $\nu_e N \rightarrow e^- X$	380	265
QE $\nu_\mu n \rightarrow \mu^- p$	11767	6462
QE $\nu_e n \rightarrow e^- p$	84	69
CC/NC Single $\pi$	22053/7741	8445/2996
CC/NC Two $\pi$	10143/3557	2394/814
CC $\nu_\tau N \rightarrow \tau^- X$	$\sim 110$	50

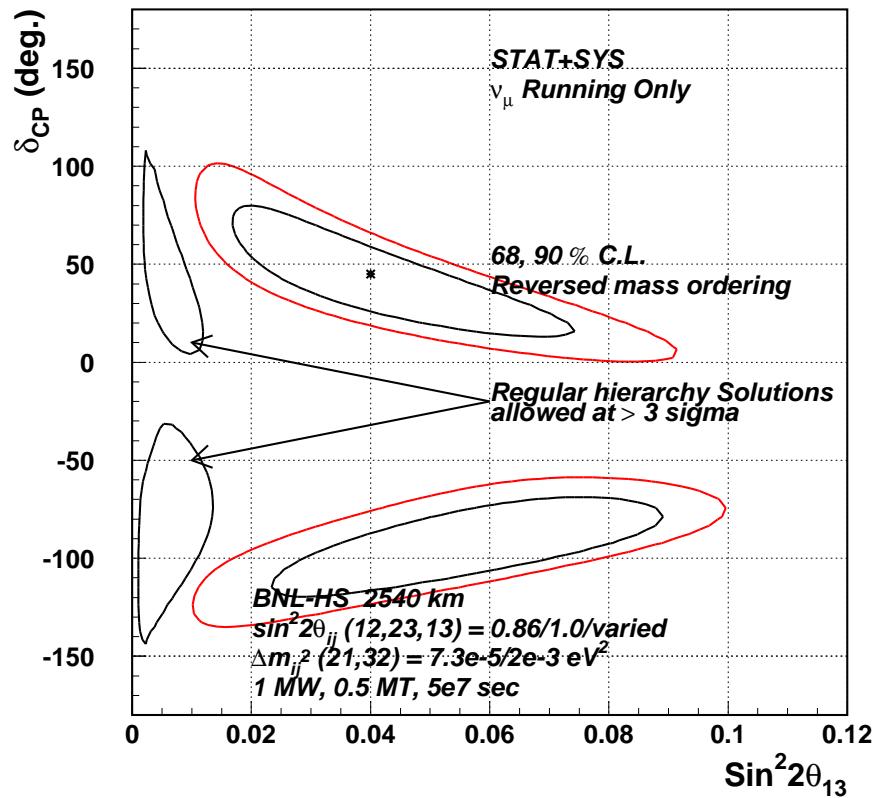
# Mass hierarchy after neutrino running

**Resolution  $\delta_{CP}$  vs  $\sin^2 2\theta_{13}$**



Left: Regular mass hierarchy

**Resolution  $\delta_{CP}$  vs  $\sin^2 2\theta_{13}$**



Right: reversed mass hierarchy.

Mass hierarchy is resolved to 3 sigma with only neutrino running in large part of the parameter space.